HIGH RESOLUTION CONVECTIVE HEAT TRANSFER MEASUREMENTS

Peter Ireland and Terry Jones
R-R UTC in Heat Transfer and Aerodynamics
Dept. Engineering Science,
University of Oxford

Acknowledgements

- Internal cooling
  - David Gillespie, Calvin Tsang, Changmin Son
- Stepped solution and fin research
  - Andrew Neely
- Recuperator research underway
  - Marty Cerza and Juan Adams
- Transition work
  - Richard Anthony

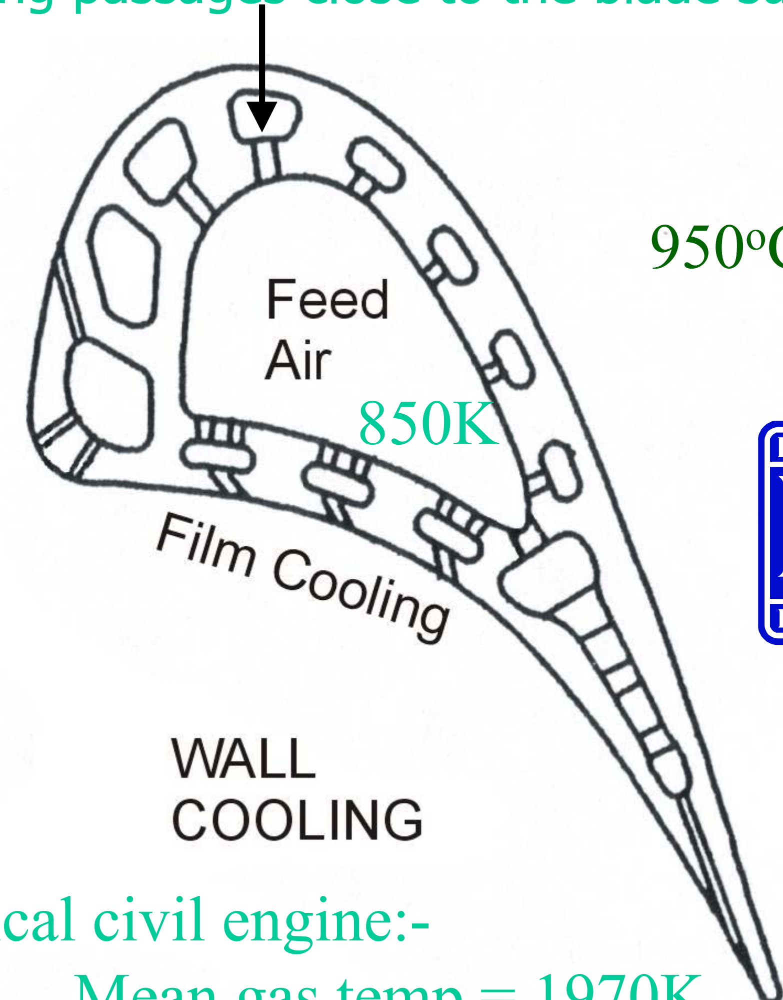
Content

- High resolution htc measurements using temperature sensitive liquid crystals
  - Need for high resolution htc data
  - Scaling strategy
  - Liquid crystal instrument features
  - Application and test details
  - Example applications new developments
- Thin film gauges
  - Instrument details and recent developments
  - Applications
  - High density platinum gauges
- Conclusions

Need for high resolution htc data in turbomachinery

- Detailed thermal model of the engine component required for component life predictions
- Aerospace turbine blades are small and cooling systems are usually compact.

Cooling passages close to the blade surface



Typical civil engine:-

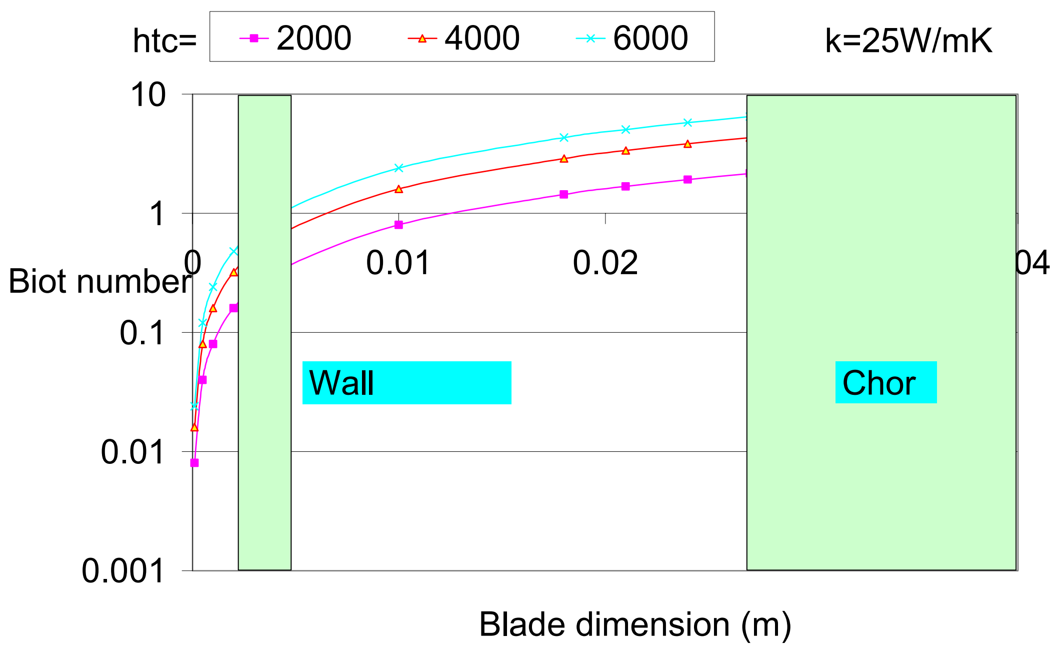
Mean gas temp = 1970K

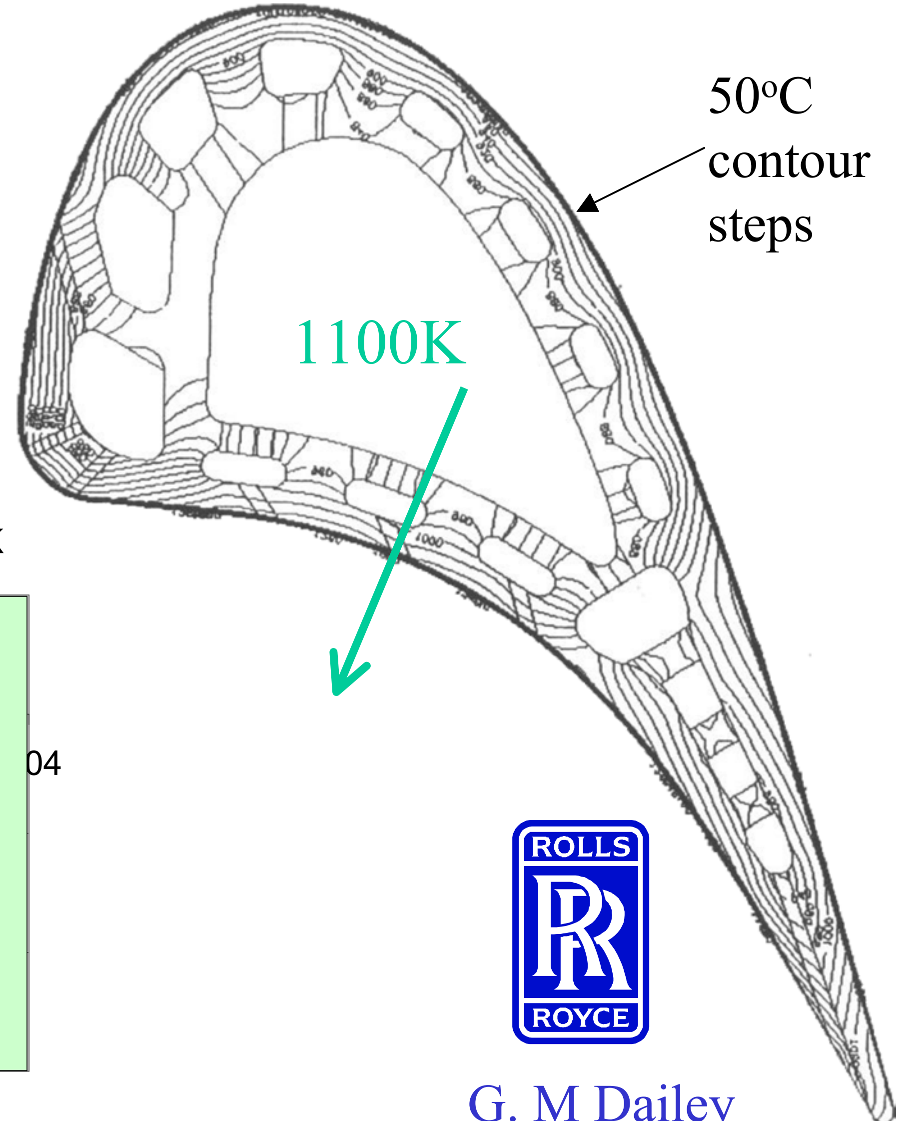
Max relative = 2375K

Example blade cooling temp distribution

- Blade far from isothermal
- Biot number not small enough

$$Biot = \frac{hL}{k}$$





G. M Dailey

Scaling issues

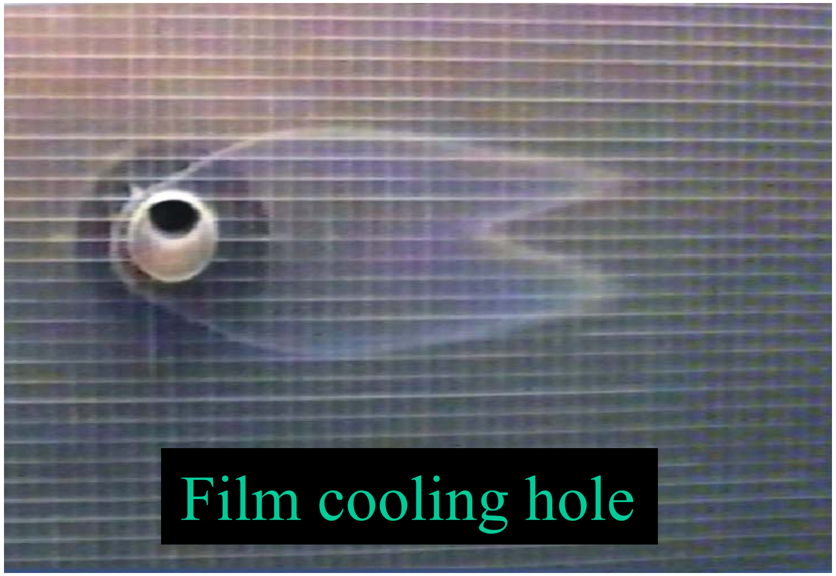
- Large scale model improves effective resolution.
- Switch off sideways (lateral) conduction to achieve local htc measurement with 1-d processing.
- No need for engine temperatures.
- Fluid dynamics correct through use of Reynolds number, Mach number and Prandtl number.

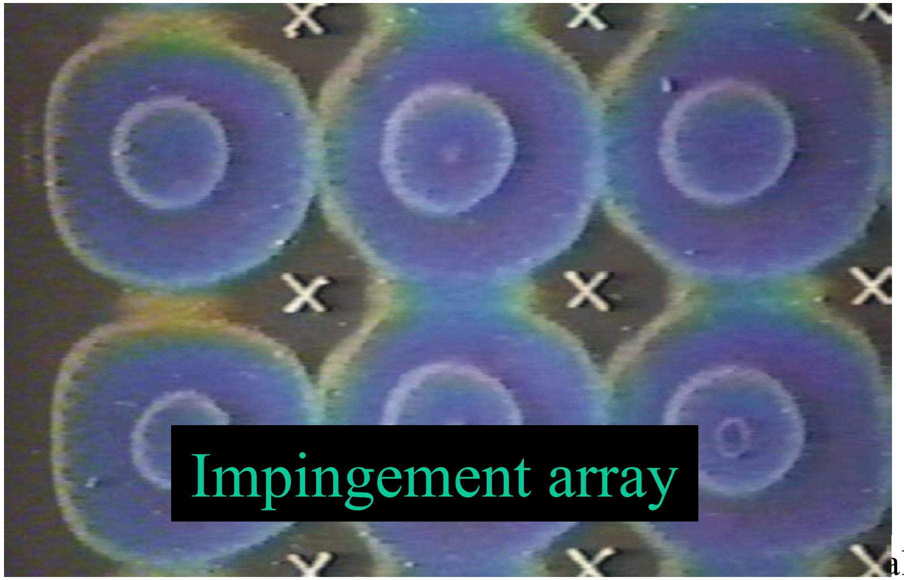
$$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Mach})$$

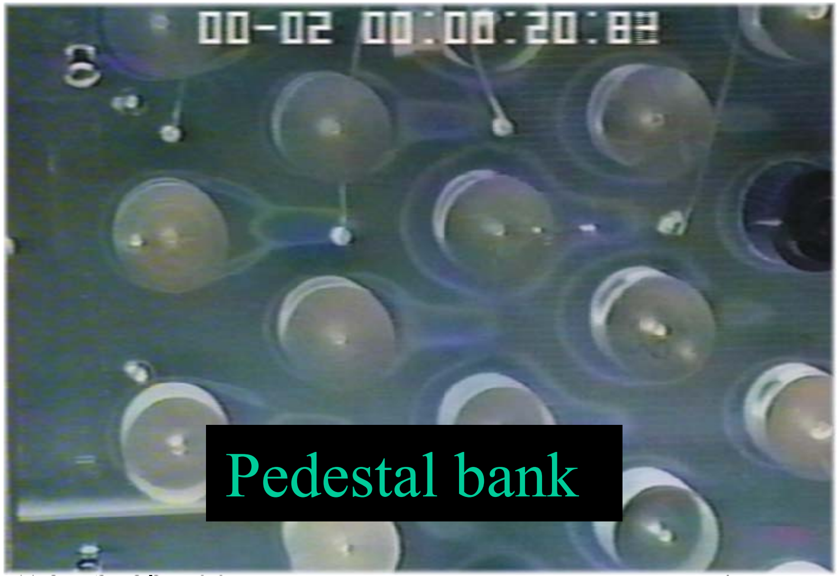
Dimensionless heat transfer coefficient

Dimensionless flow speed

Transient method with liquid crystals for internal cooling

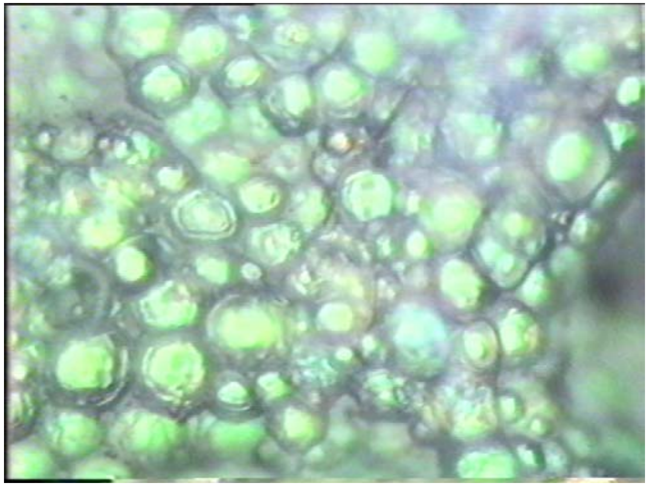






als

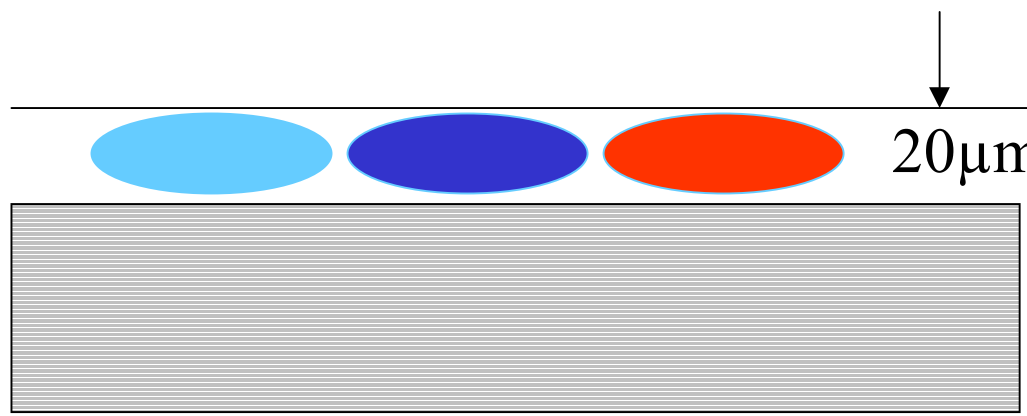
Temperature measurement



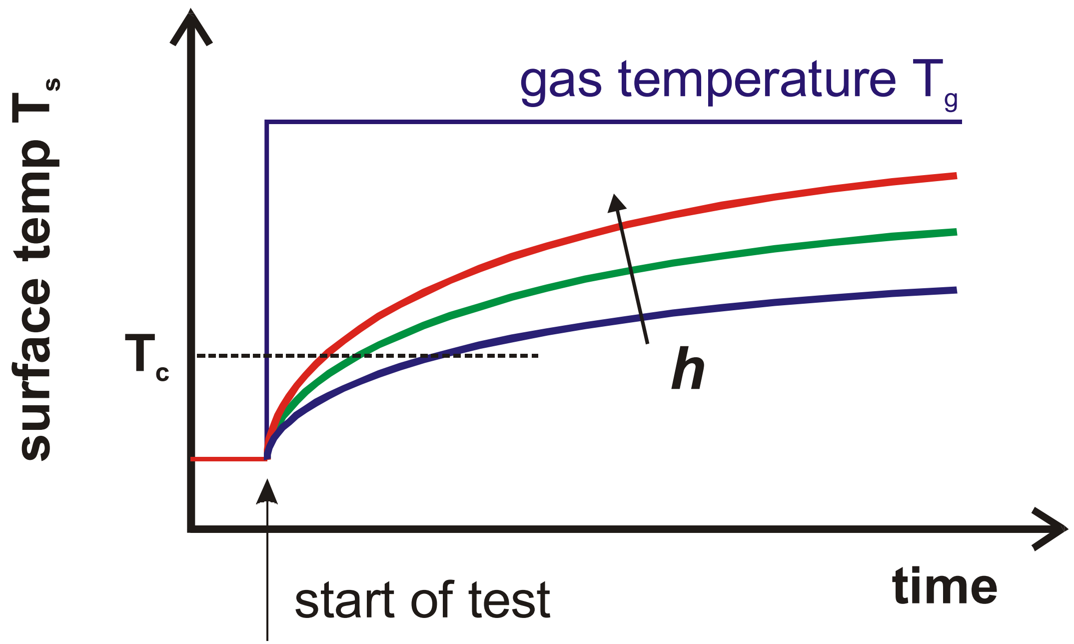
Red **G**reen **B**lue signals from video
→ **I**ntensity or **H**ue processing

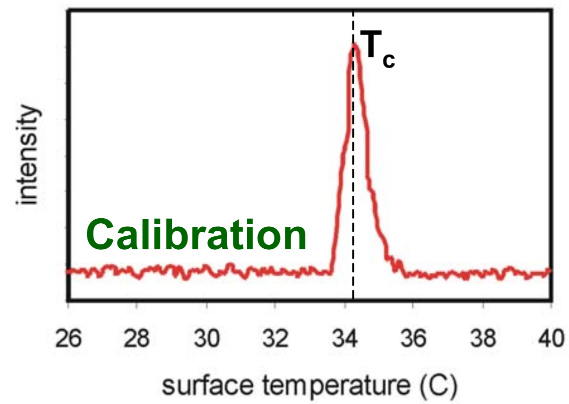
$$I = R + G + B$$

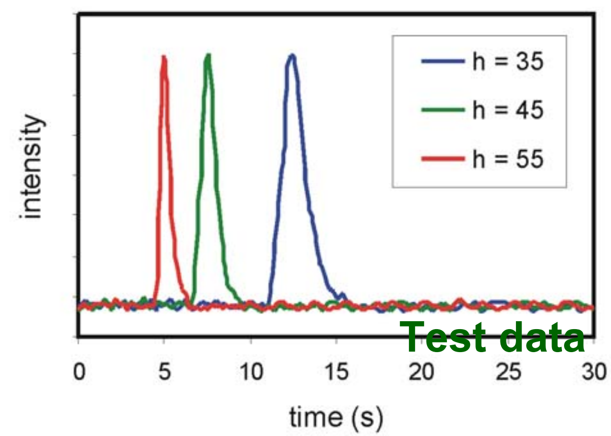
$$\cos(H) = \frac{2R - G - B}{\sqrt{6((R - I)^2 + (G - I)^2 + (B - I)^2)}}$$



Time of crystal colour change depends on local *h*

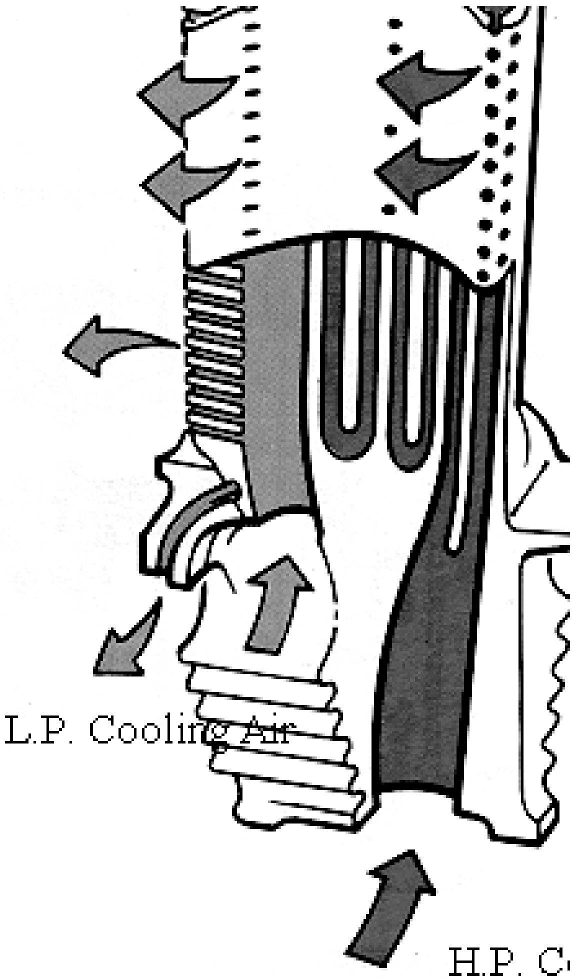


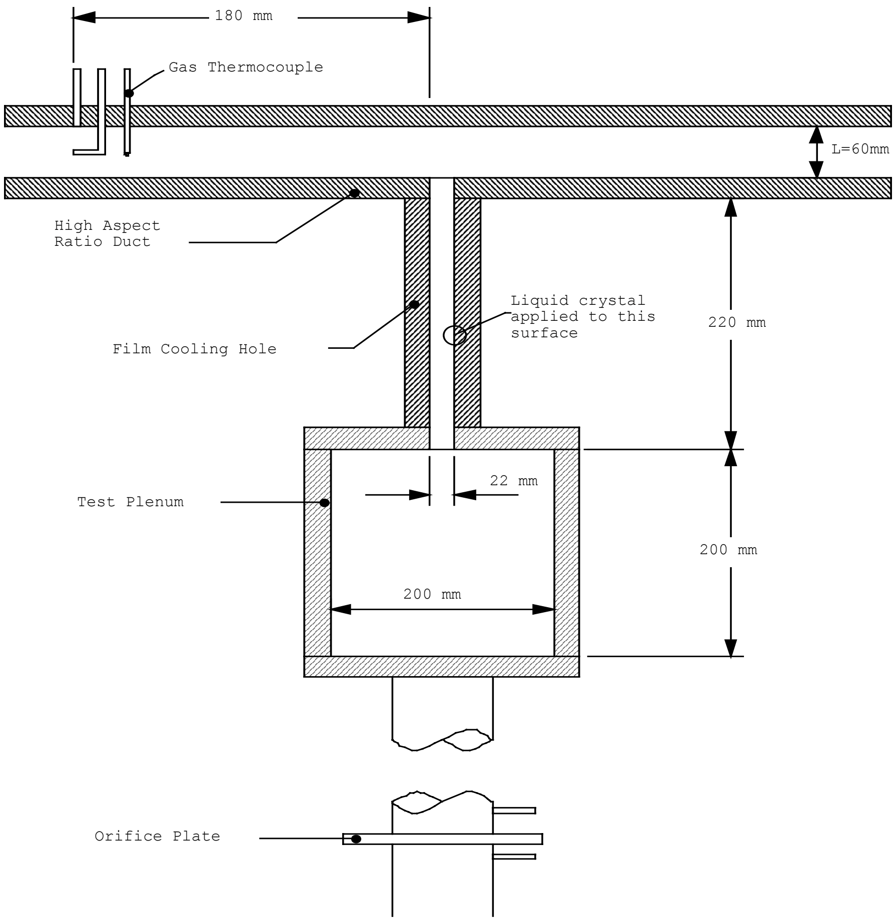




Heat transfer inside a film-cooling hole fed in cross-flow

Hole diameter = 0.3mm

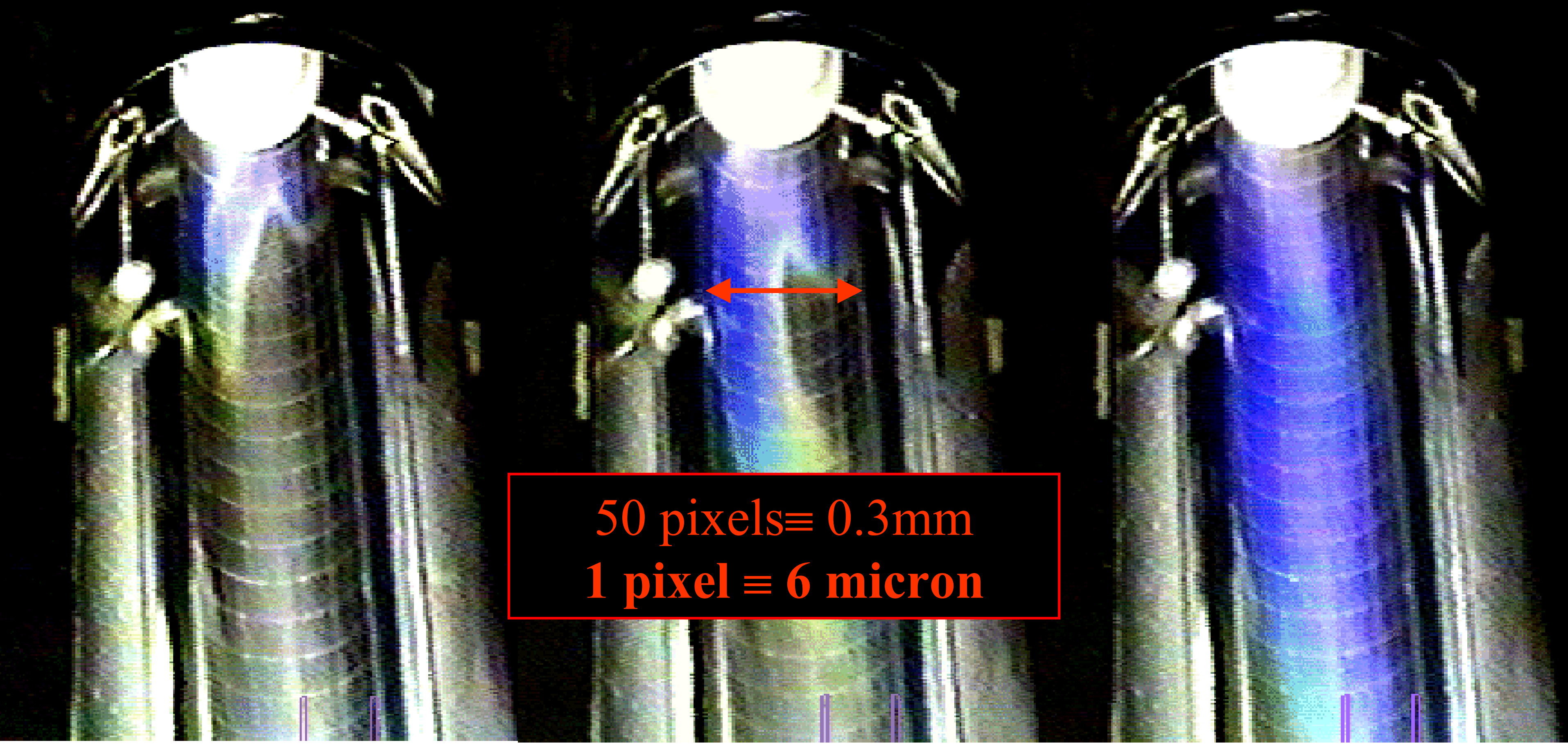




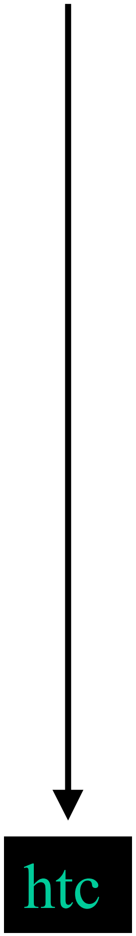
Hole diameter = 22mm

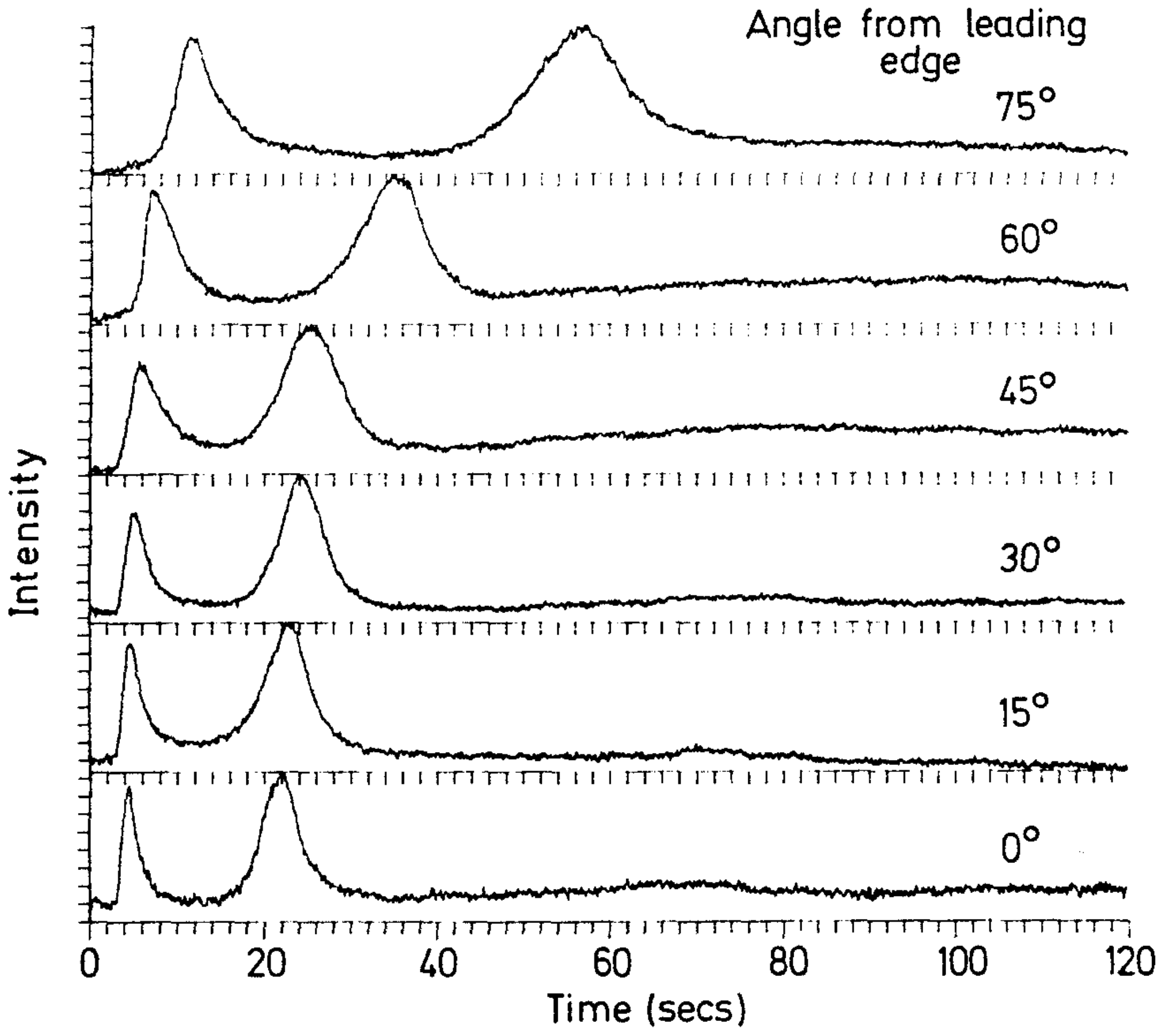
:00:11:65 :00:16:19 :00:22:15

Recorded Colour Play within the Hole

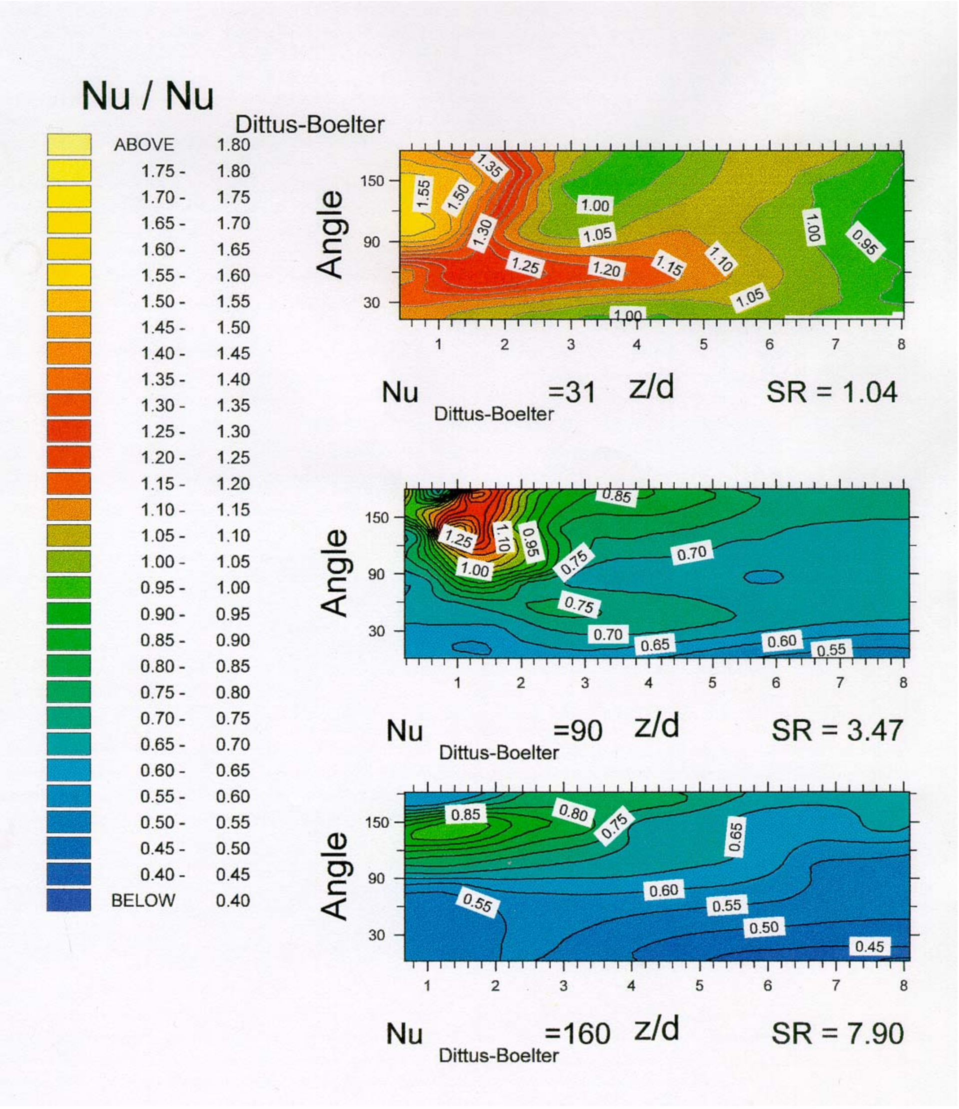


Typical Intensity Histories at 6 Positions on the Film Cooling Hole Surface. Monochromatic processing.



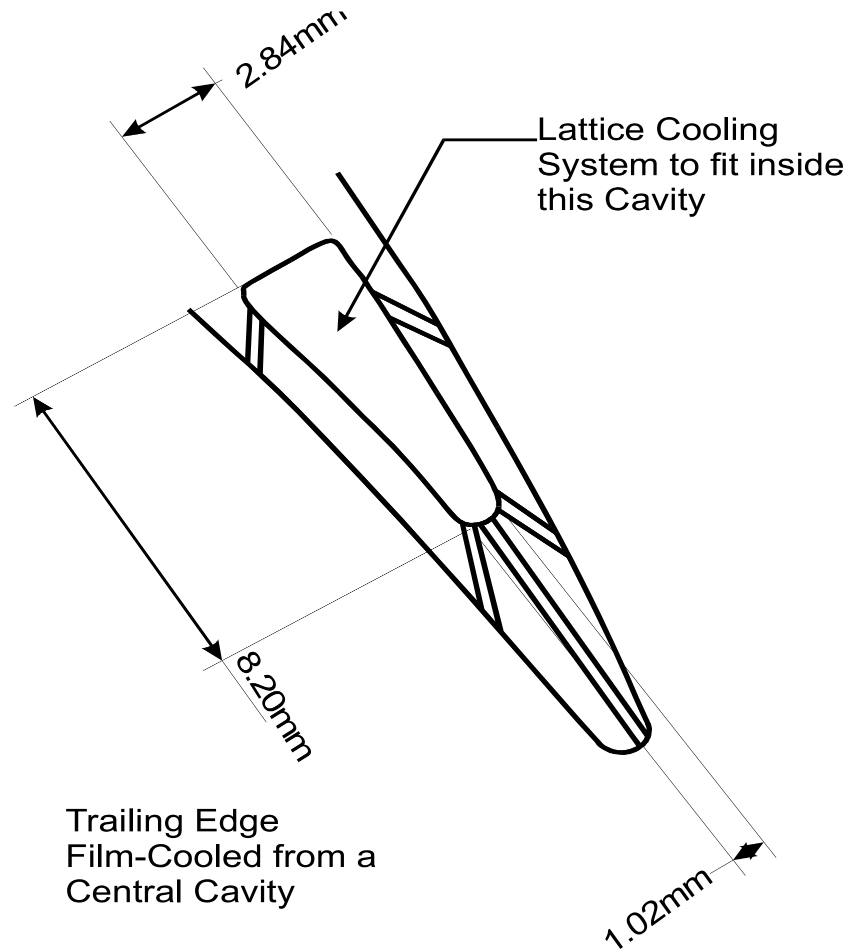


Local Nusselt Number Distribution, 90^o Hole

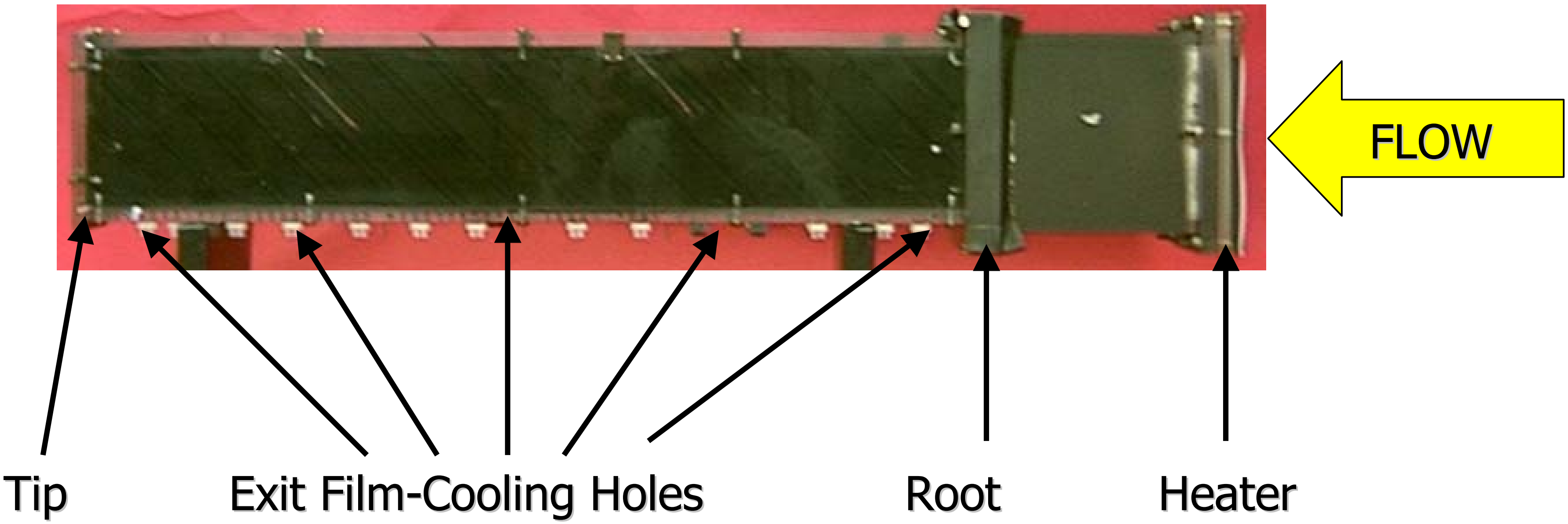


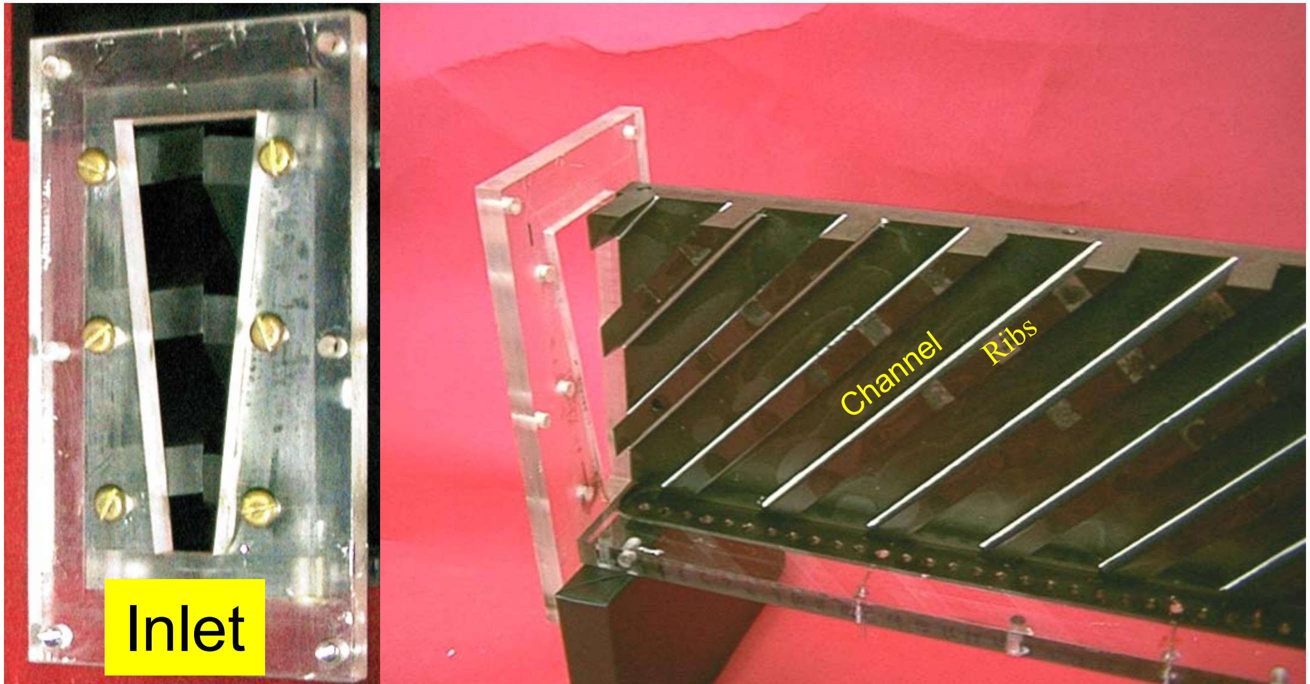
Lattice cooling system for trailing edge

Geometric scaling essential for resolution

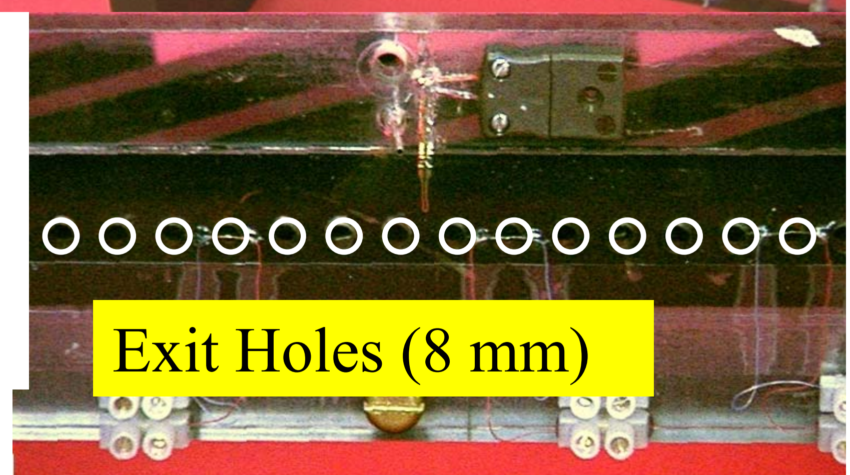


The Assembled Lattice Model

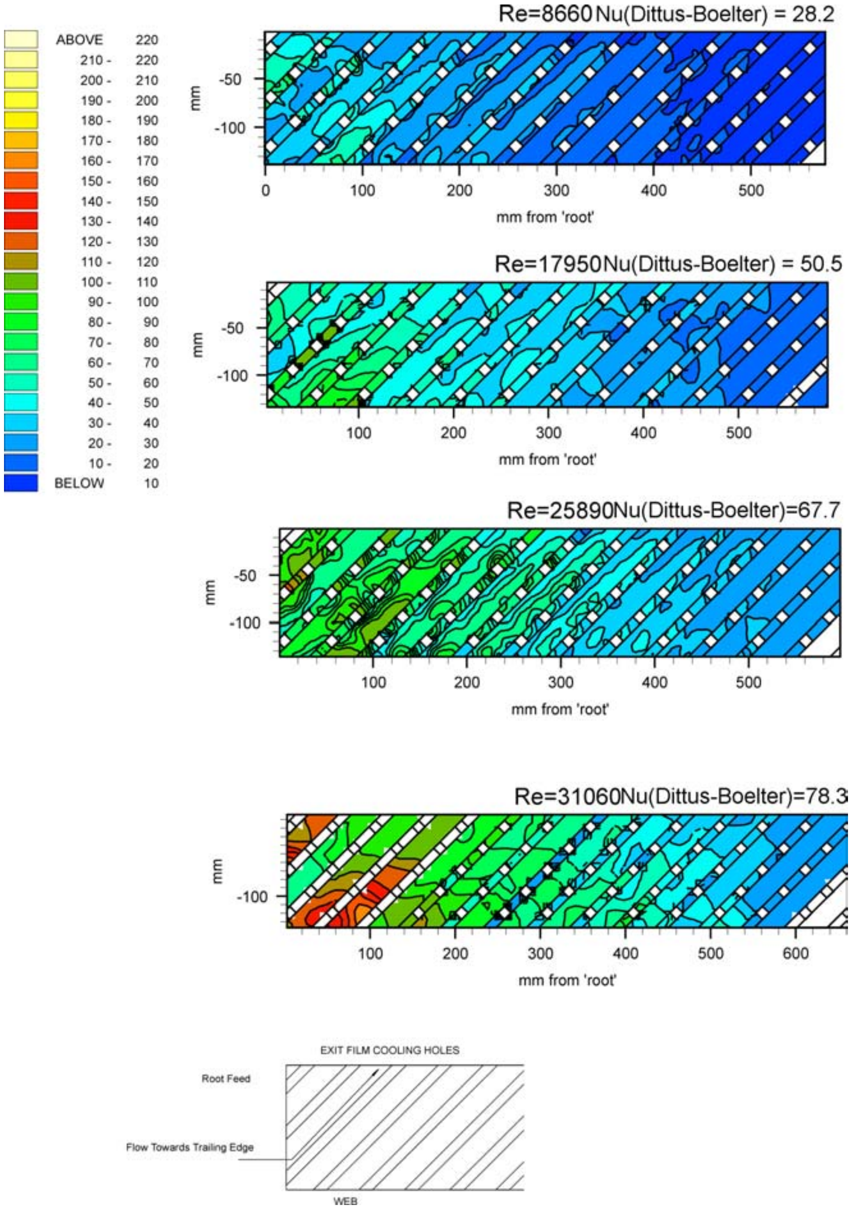


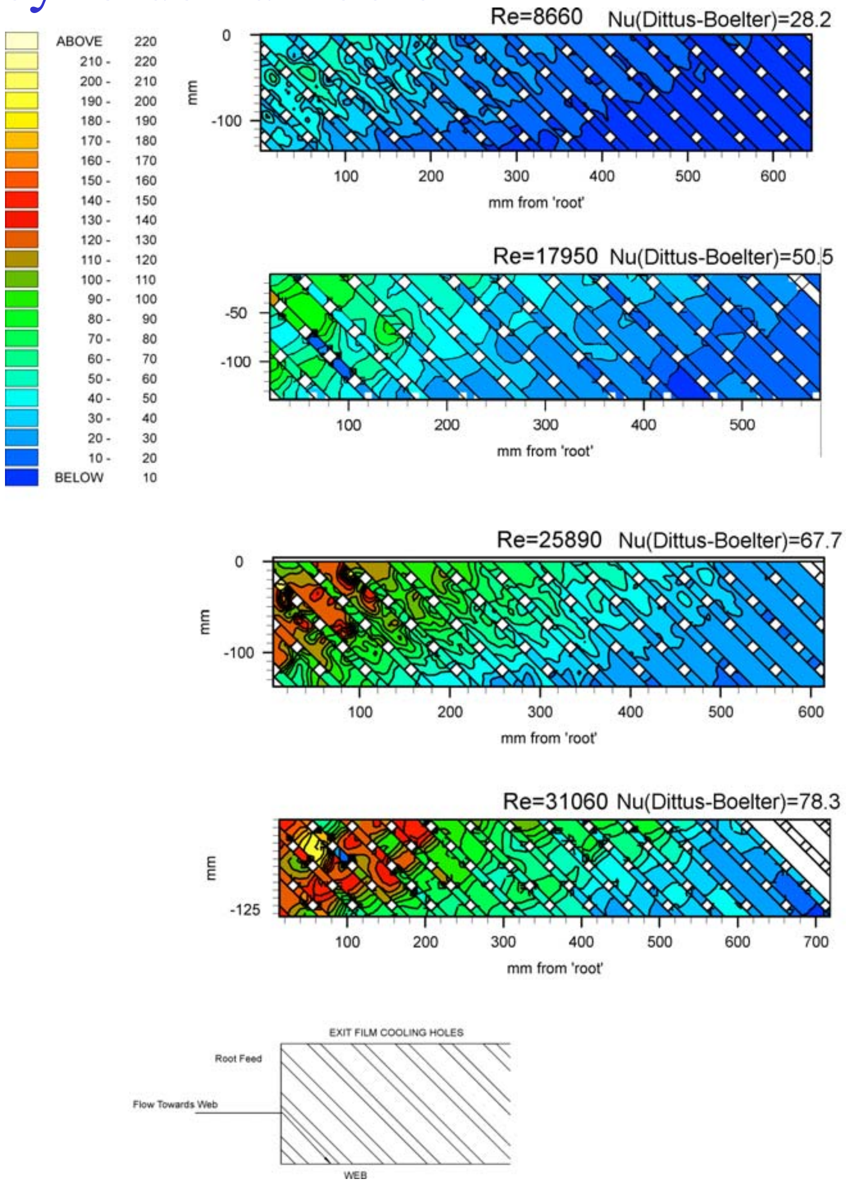


Photographs of the Working Section



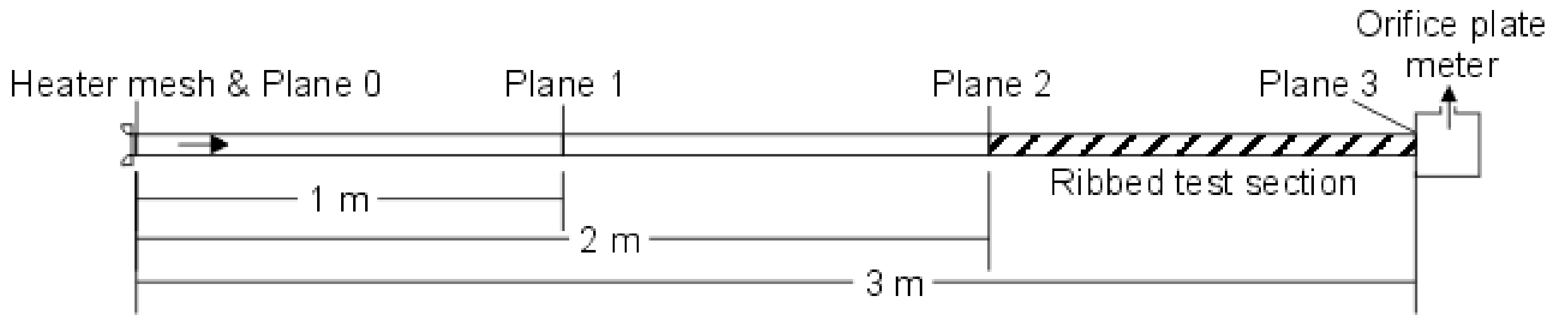
Nusselt number distribution at several Reynolds numbers





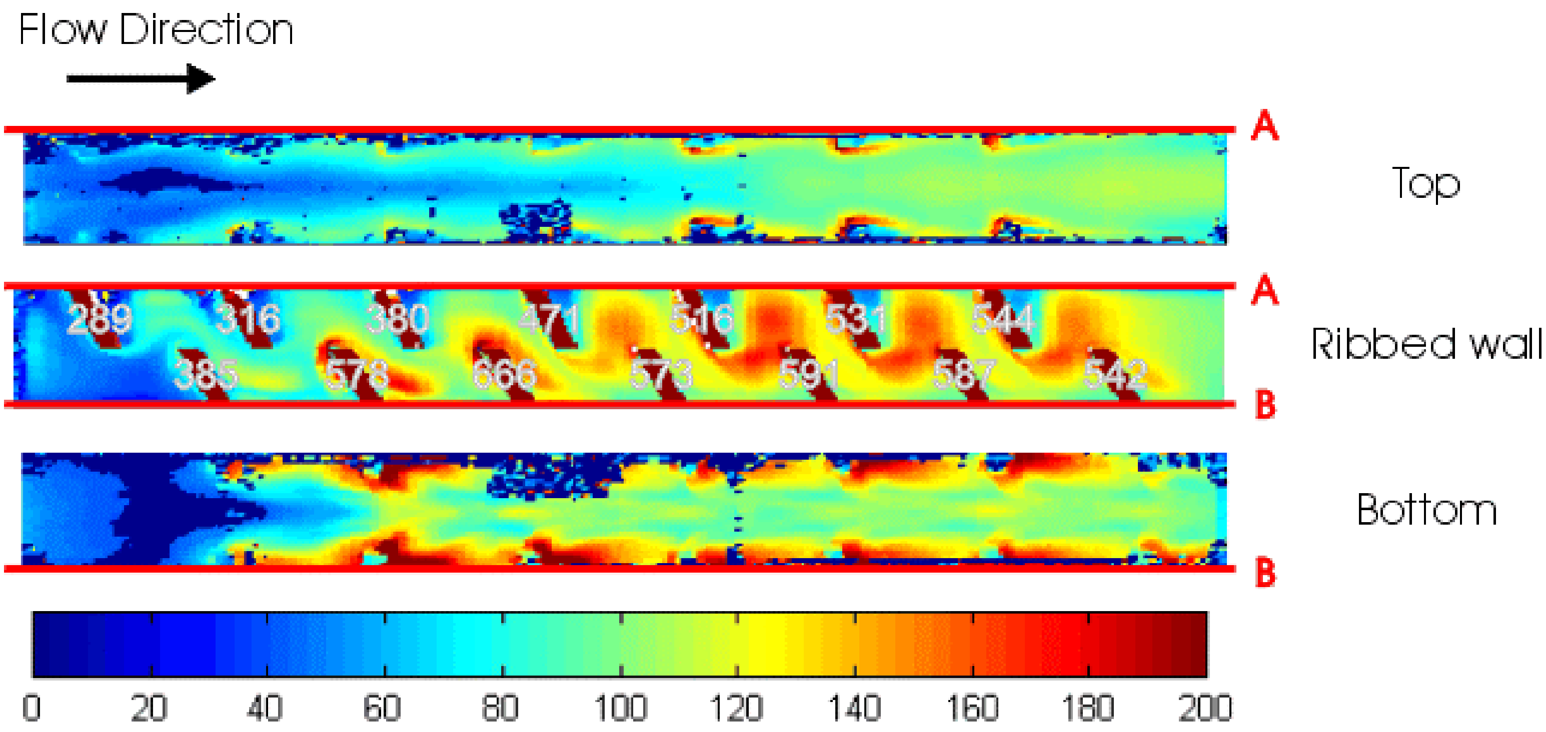
Rib roughened passage

- 3 metres (60d) long, square cross section cooling passage
- Perspex walls with temperature sensitive liquid crystal coated on the inner surface.
- Reynolds number from 20,000 to 60,000
- Air is heated at the inlet using heater mesh
- Test section situated from 40d to 60d
- Fully developed flow established ahead of the test section
- Rotation not simulated in the experiment

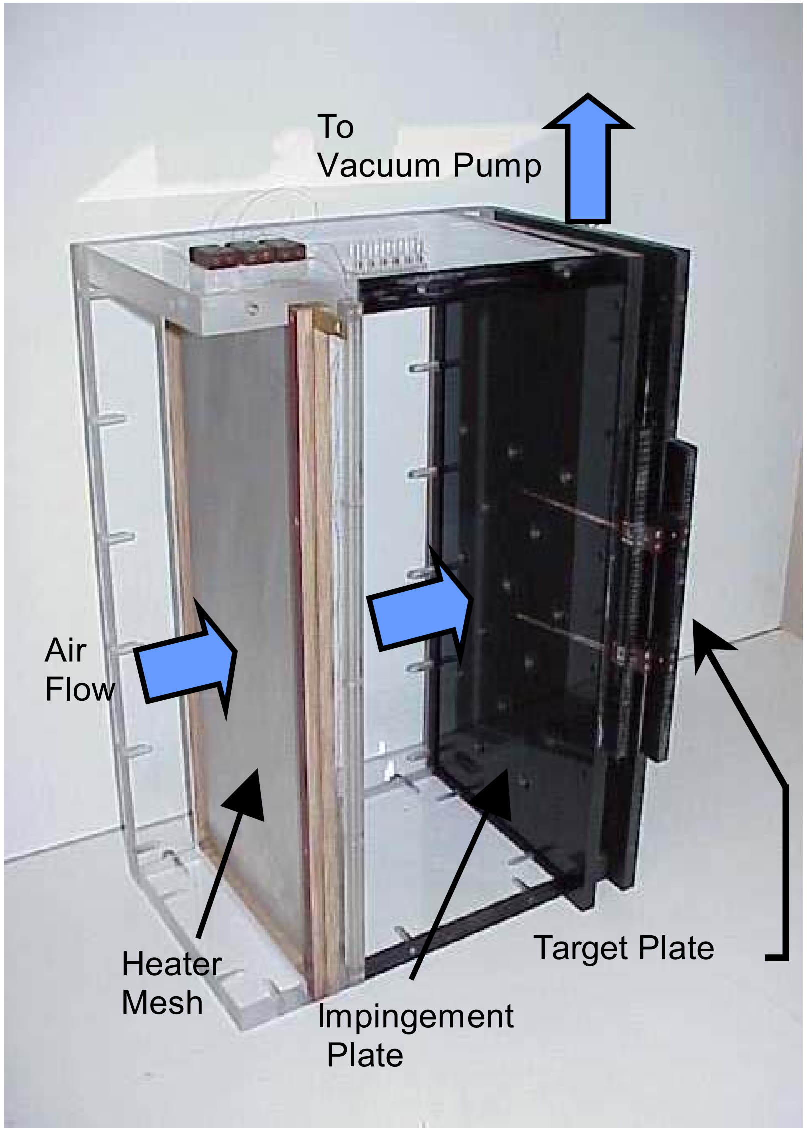


Heat transfer distribution

60° interrupted inline ribs

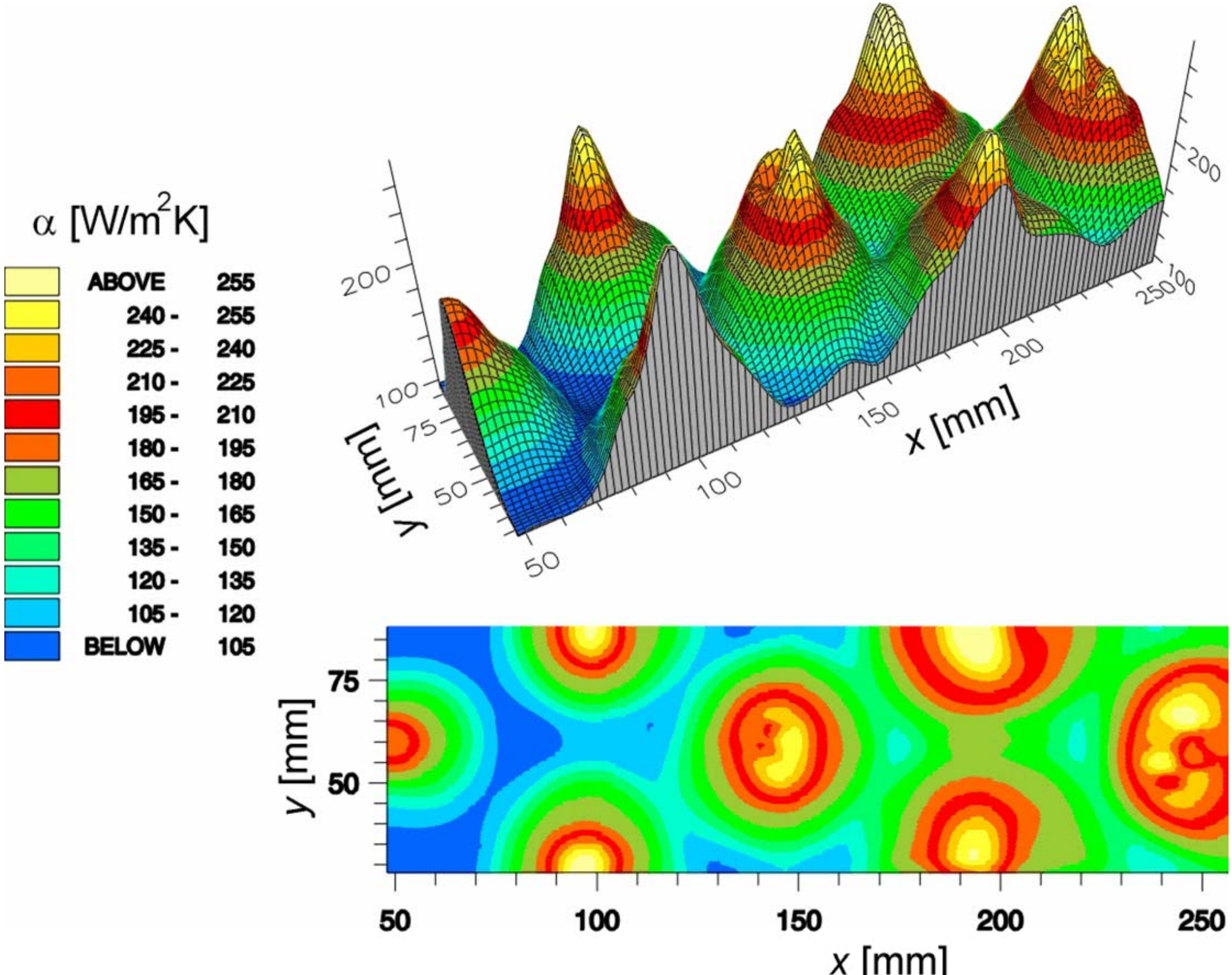


Impingement heat transfer rig



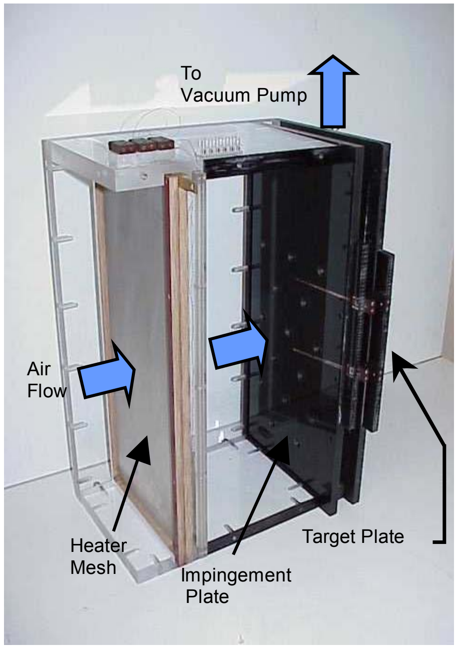
The perspex test rig is instrumented with liquid crystal coated impingement and target plates, and fast response gas thermocouples at the entrance and exit of the working section

Impinging jet heat transfer



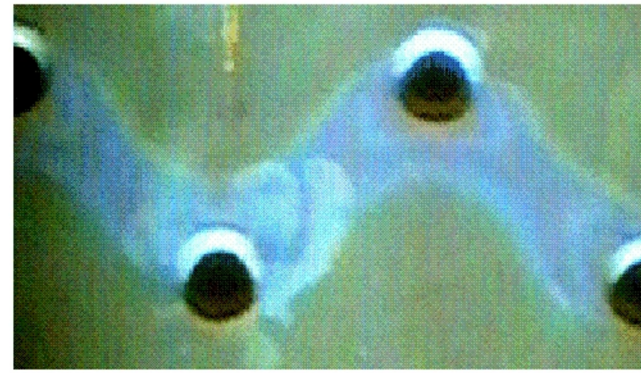
Re_{javg} = 26710

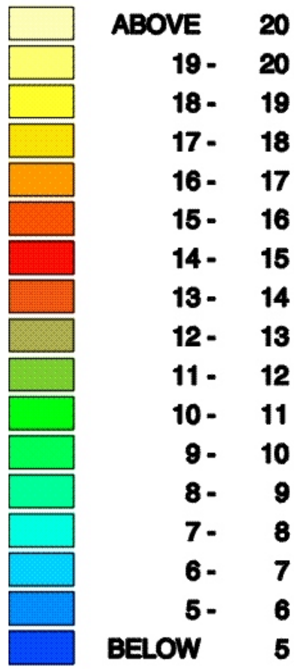
Data through the mesh heater



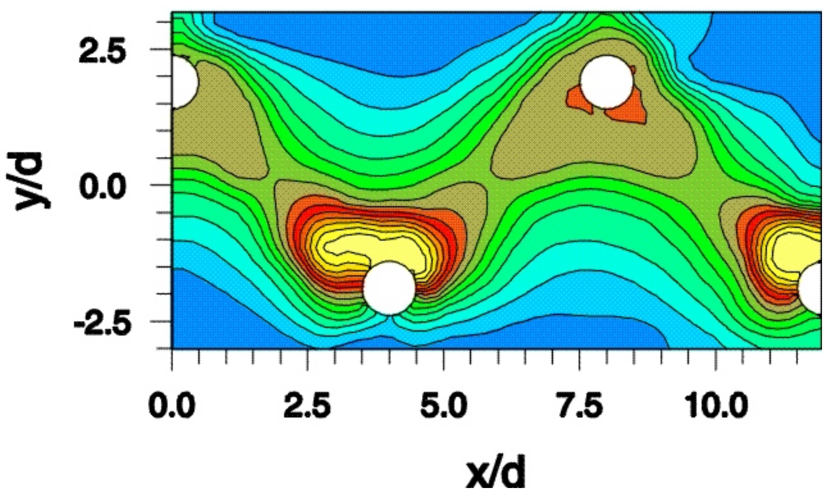
Reynolds Number = 38000

Image at time = 60 seconds

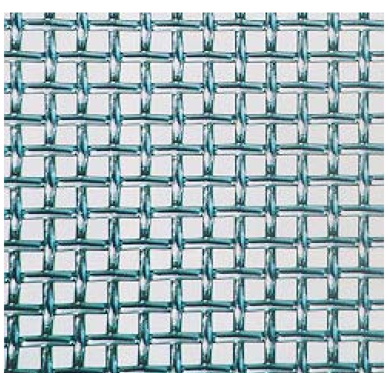




Nusselt Number



60µm square apertures

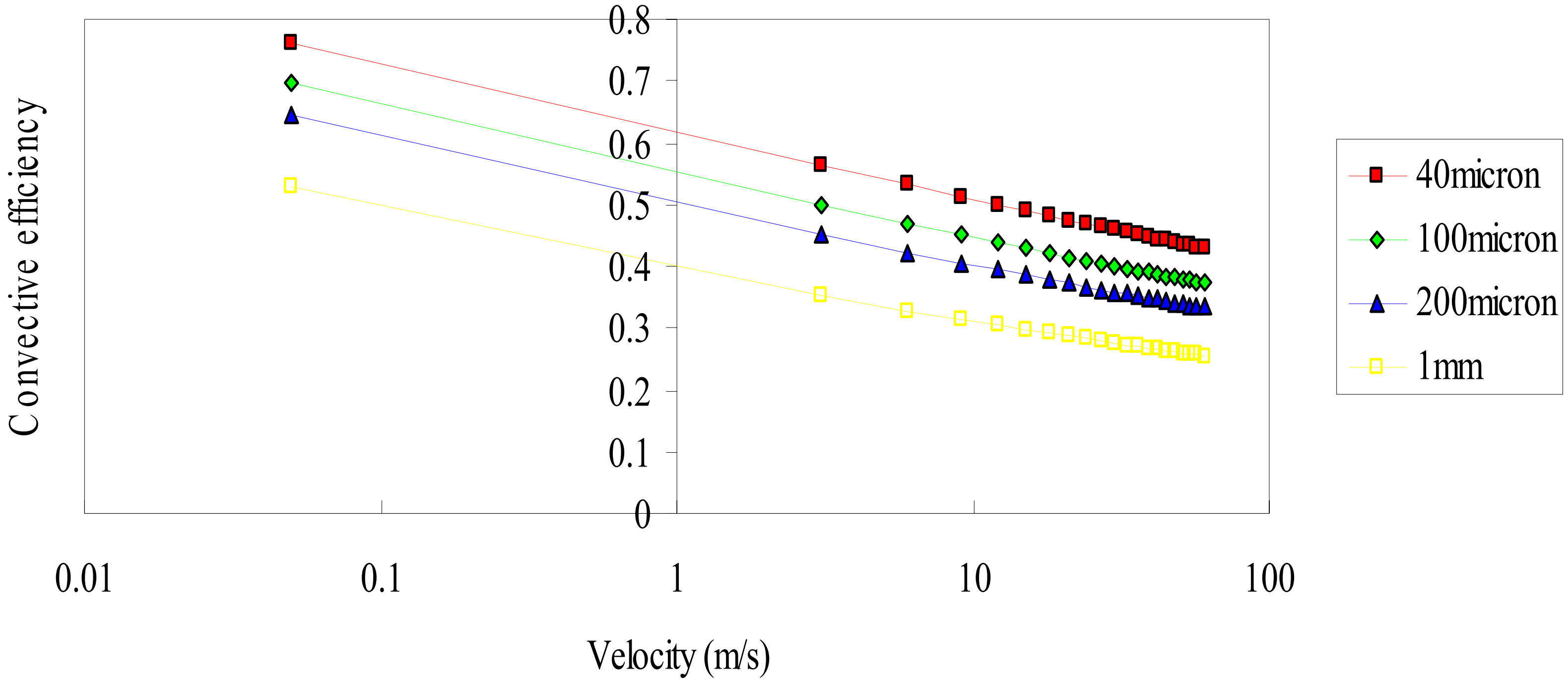


Heater convective efficiency

- High convective efficiency (~50%) so:
  - –wires run cool
  - –radiation insignificant
  - –support easy to engineer

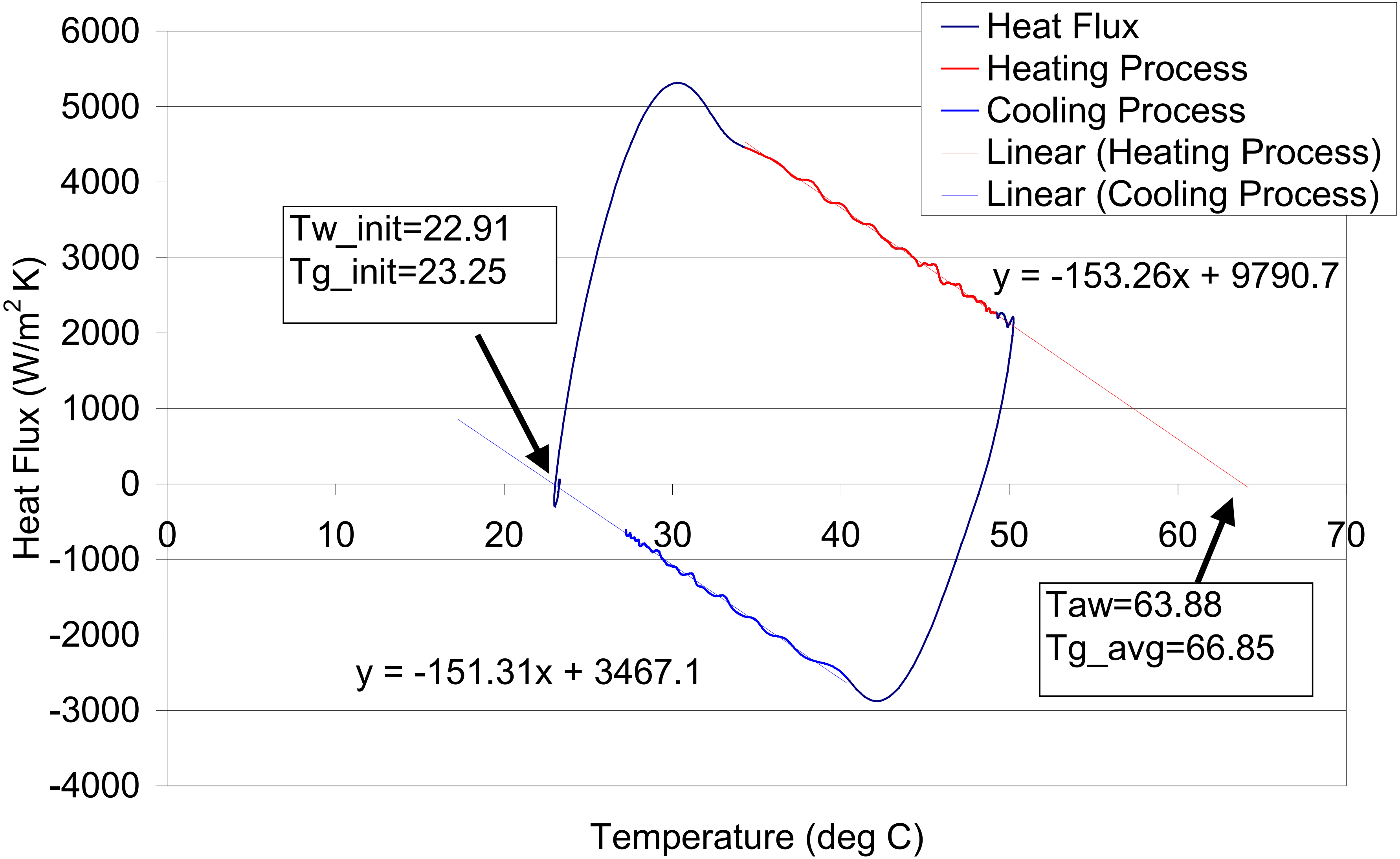
$$\eta_{CONVECTIVE} = \frac{T_{wire} - T_{downstream}}{T_{wire} - T_{upstream}}$$

- Suitable for switching temperature of low speed flows

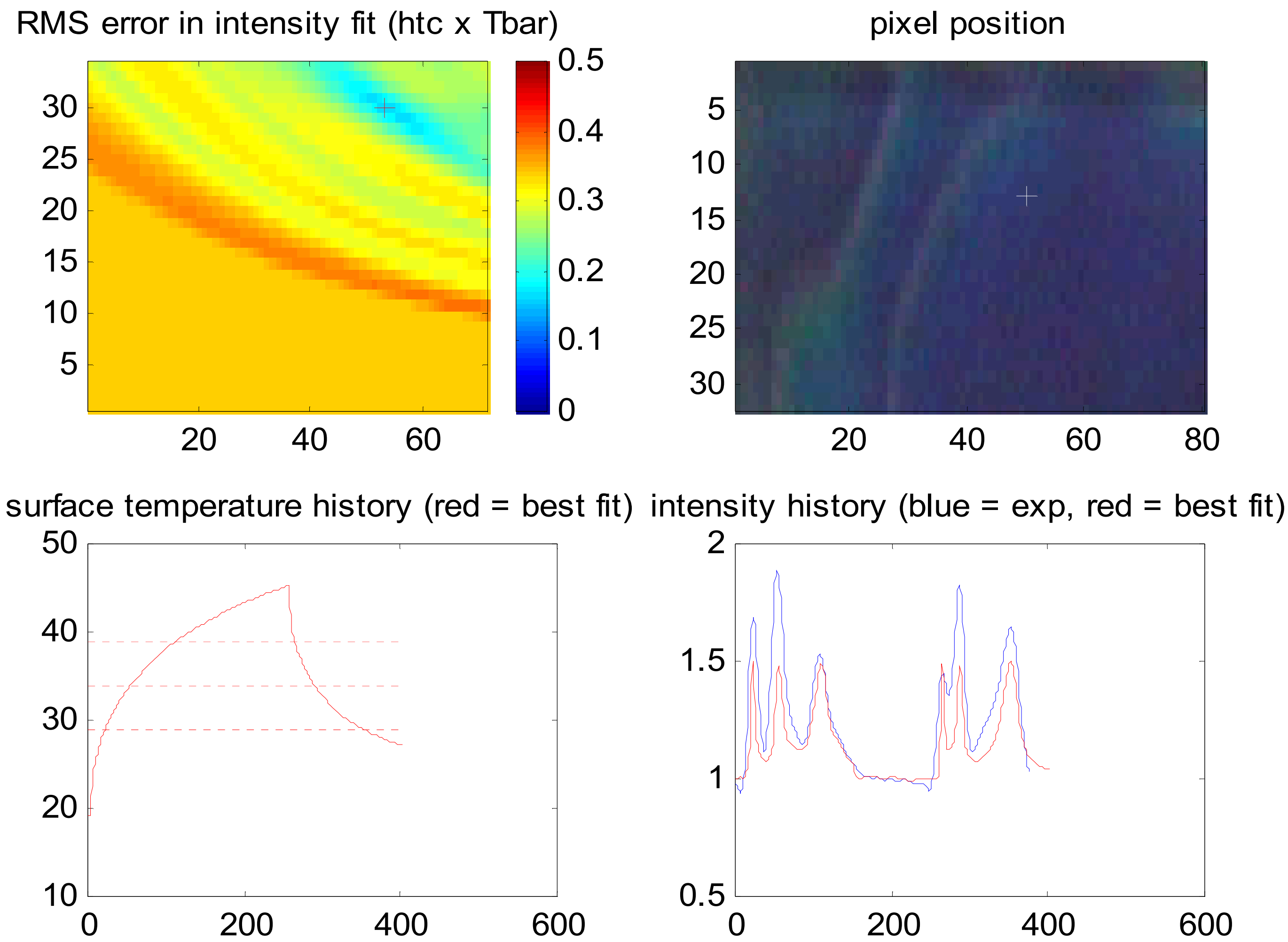


Fluid temperature	**Surface temperature**
Step change to T_g	$T_s = T_0 + \left(T_g - T_0\right)\left(1 - \exp(\frac{h^2 t}{\rho c k}) \times erfc(\frac{h\sqrt{t}}{\sqrt{\rho c k}})\right)$
Series of steps	$T_s = T_0 + \sum_{i=1}^{n} \left(T_{g_i} - T_{g_{i-1}}\right)\left(1 - \exp(\frac{h^2 (t - \tau_i)}{\rho c k}) erfc(\frac{h\sqrt{t - \tau_i}}{\sqrt{\rho c k}})\right)$
Exponential with asymptote T_g	$\frac{T_s - T_0}{T_g - T_0} = 1 - \frac{\frac{\rho c k}{h^2 \tau}}{\left(1 + \frac{\rho c k}{h^2 \tau}\right)} e^{\frac{h^2 t}{\rho c k}}$ $\mathrm{erfc}\left(\frac{\mathrm{h}\sqrt{\mathrm{t}}}{\sqrt{\rho c k}}\right) - e^{-\frac{t}{\tau}} \frac{1}{\left(1 + \frac{\rho c k}{h^2 \tau}\right)}$ $\left(1 + \frac{\sqrt{\rho c k}}{h\sqrt{\tau}}\left(\frac{1}{\pi}\sqrt{\frac{t}{\tau}} + \frac{2}{\pi}\sum_{1}^{\infty}\frac{1}{n} e^{-\frac{n^2}{4}} \sinh n\sqrt{\frac{t}{\tau}}\right)\right)$
Ramp function with slope m	$T_s = T_0 + mt\left\{1 - \frac{2}{\beta} + \frac{1 - \exp(\beta^2) erfc(\beta)}{\beta^2}\right\}$

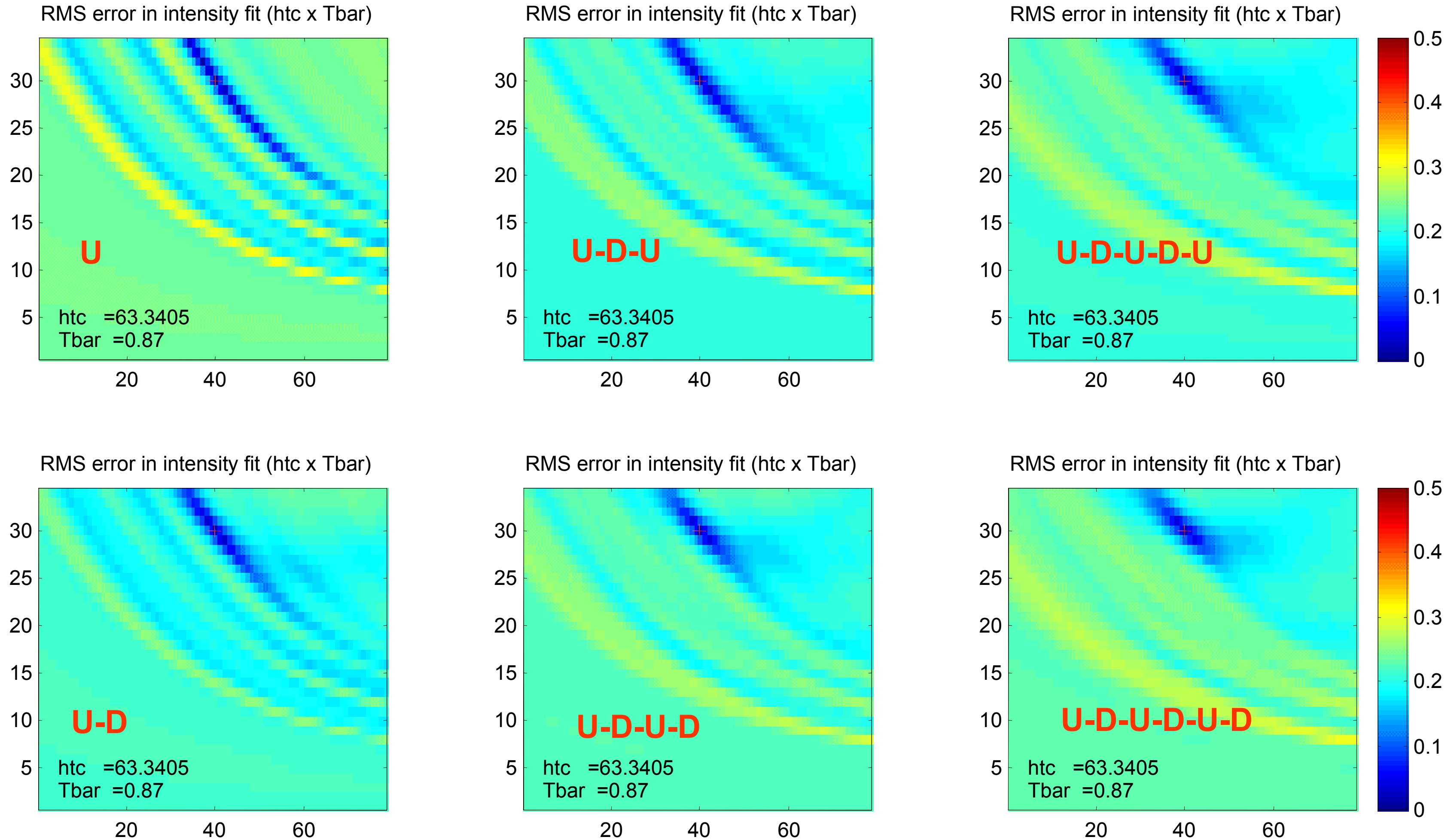
Works heating or cooling



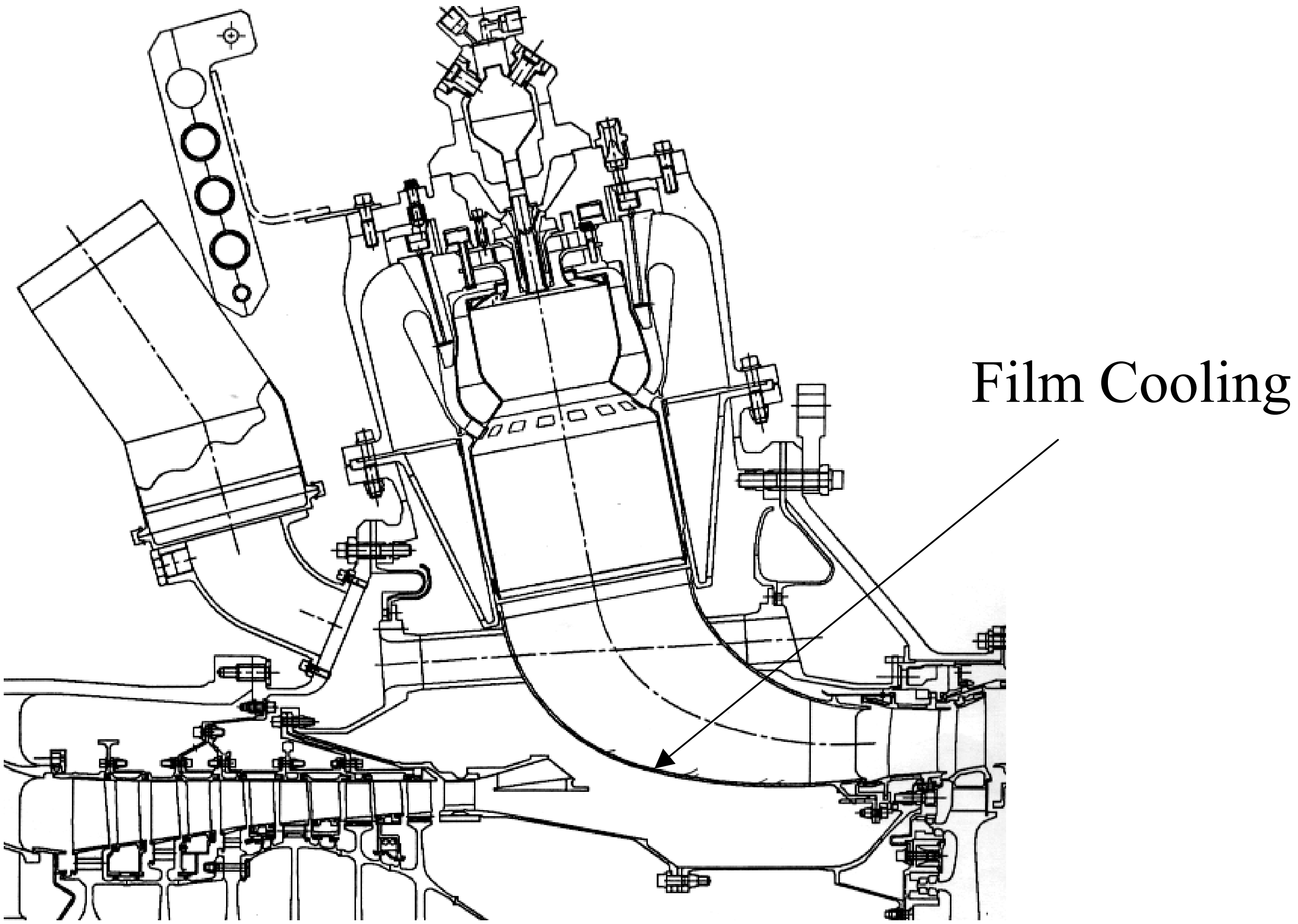
Use of stepped flow temperature



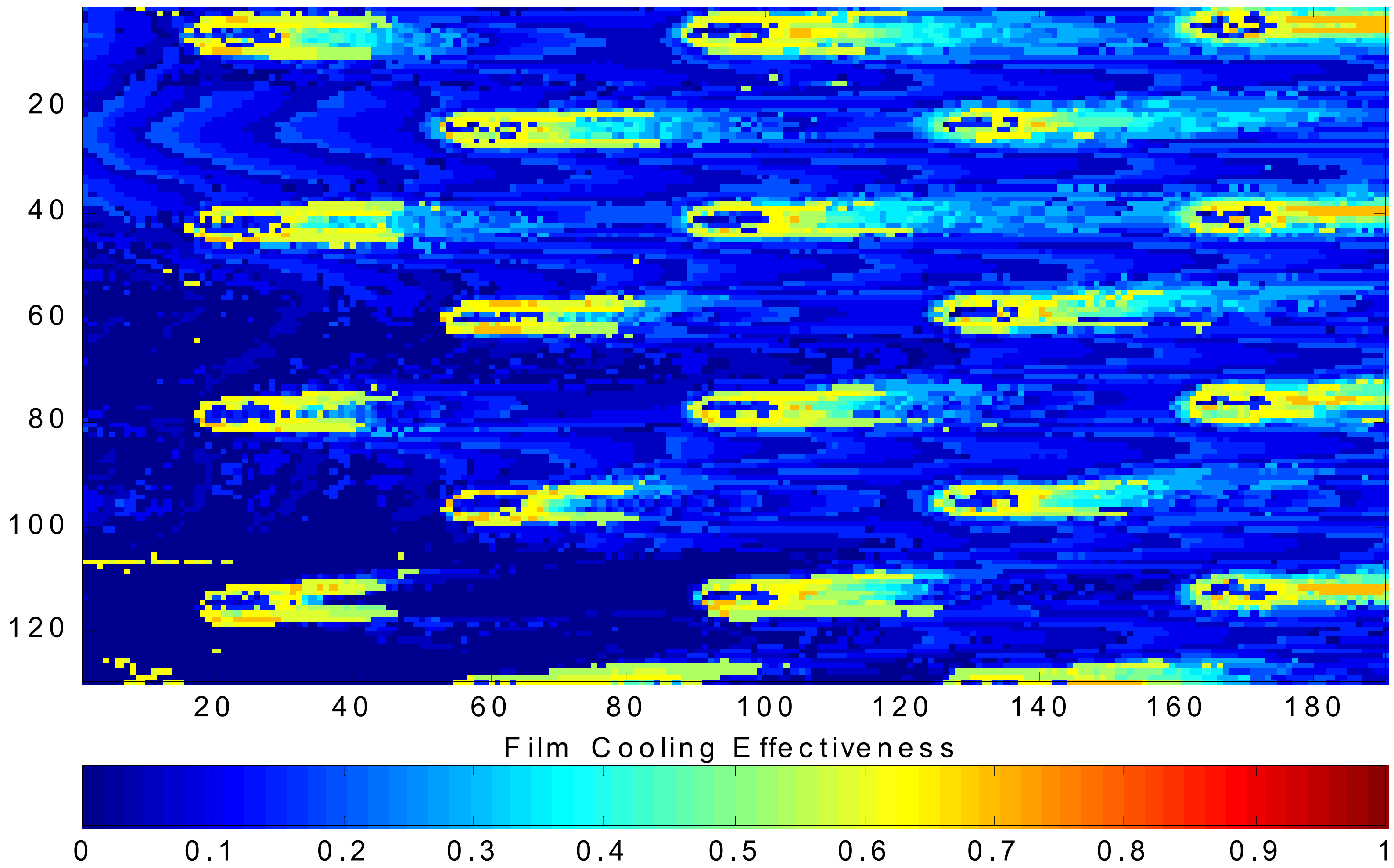
Increasing the number of steps



Work on Dry Low Emission Combustor



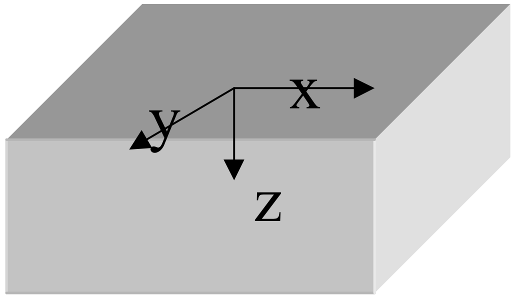
Film Cooling Effectiveness



Lateral Conduction Correction

Step Two: Alternating Direction Methods (after Jim Douglas)

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$



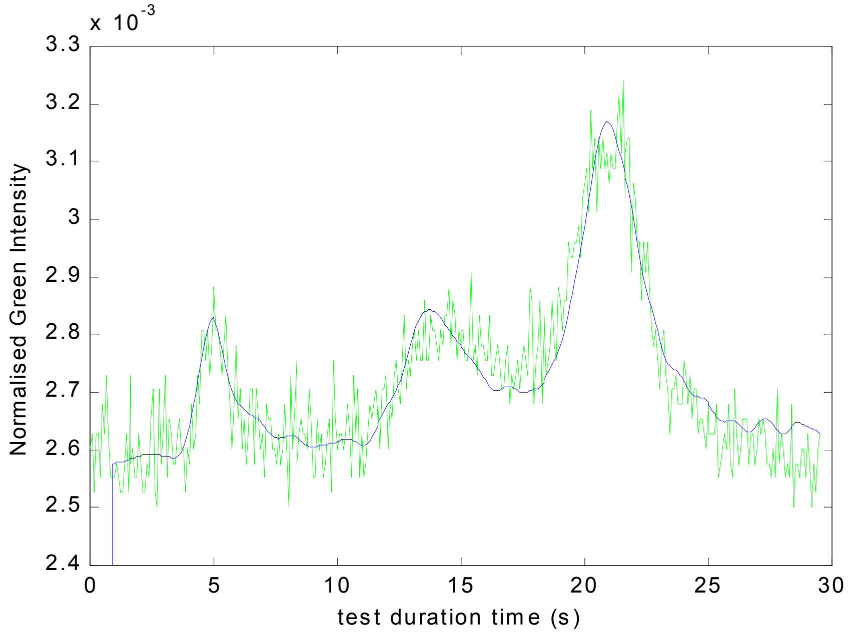
a) $$(\Delta_x^2 - \frac{2}{\Delta t})T_{n+1}^{*} = -(\Delta_x^2 + 2\Delta_y^2 + 2\Delta_z^2 + \frac{2}{\Delta t})T_n$$

b) $$(\Delta_y^2 - \frac{2}{\Delta t})T_{n+1}^{**} = \Delta_y^2 T_n - \frac{2}{\Delta t}T_{n+1}^{*}$$

c) $$(\Delta_z^2 - \frac{2}{\Delta t})T_{n+1} = \Delta_z^2 T_n - \frac{2}{\Delta t}T_{n+1}^{**}$$

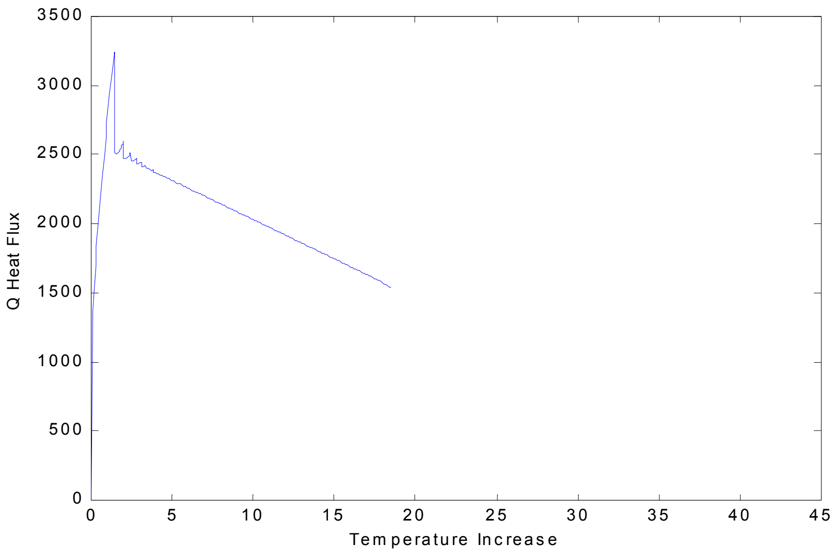
where $\Delta_x^2 T_{i,j,k,n} = (T_{i+1,j,k,n} - 2T_{i,j,k,n} + T_{i-1,j,k,n})/(\Delta x)^2$

Lateral Conduction



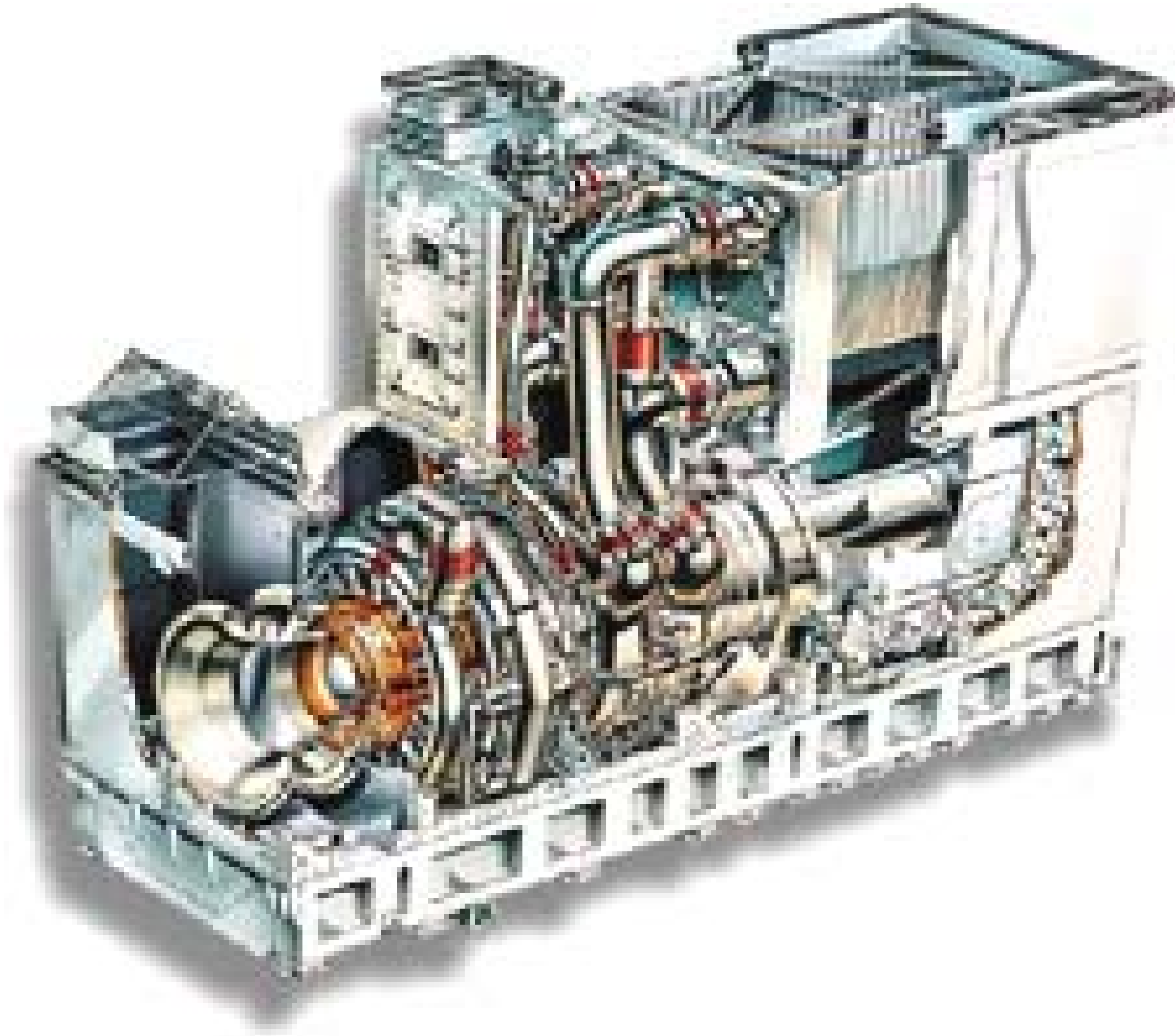
Heat Flux at each pixel can be then be calculated. The Film Cooling Effectiveness and Heat Transfer Coefficient can be determined by the interception of the

Temperature axis and the gradient of the heat flux graph shown above.



Current marine application

- 832 channels in the specimen.
- Length of each channel: 197 mm.



RR spiral recuperator

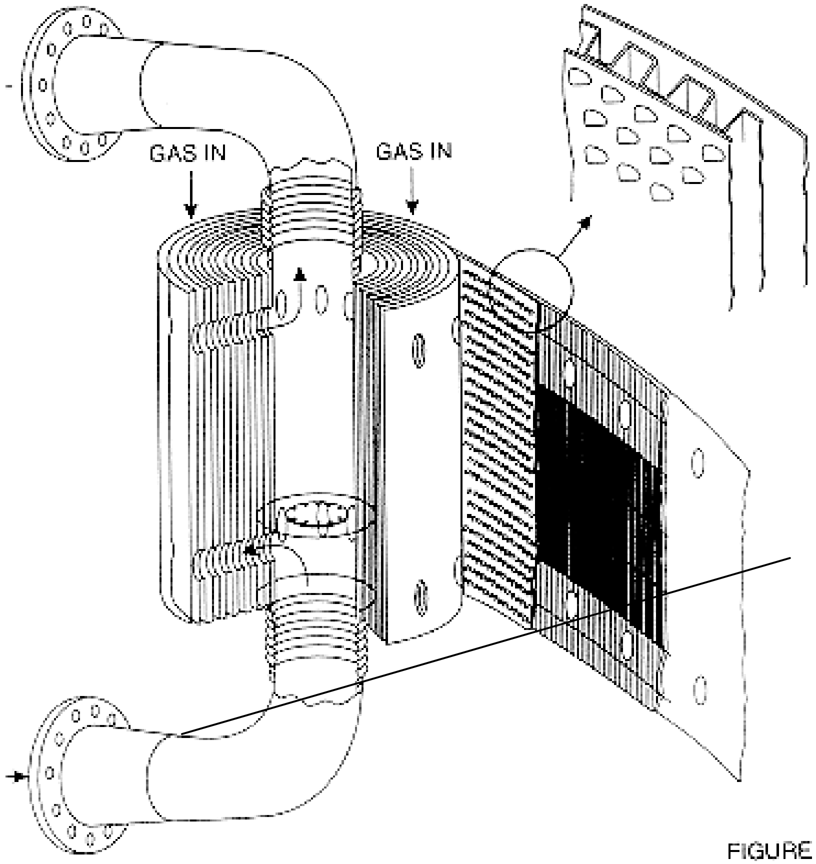


FIGURE 2

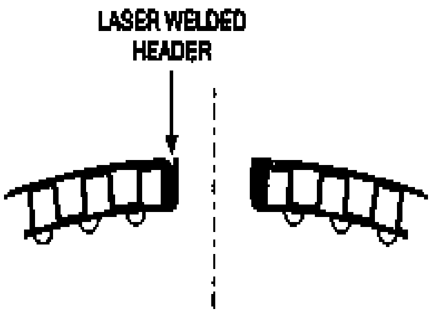


FIGURE 5

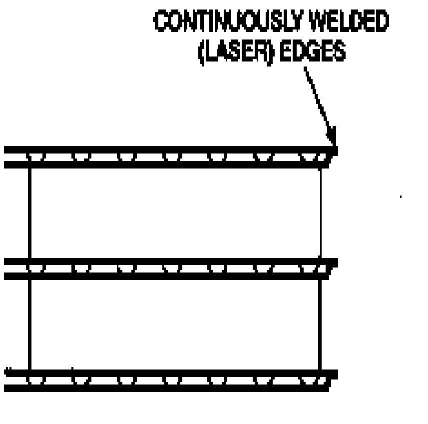
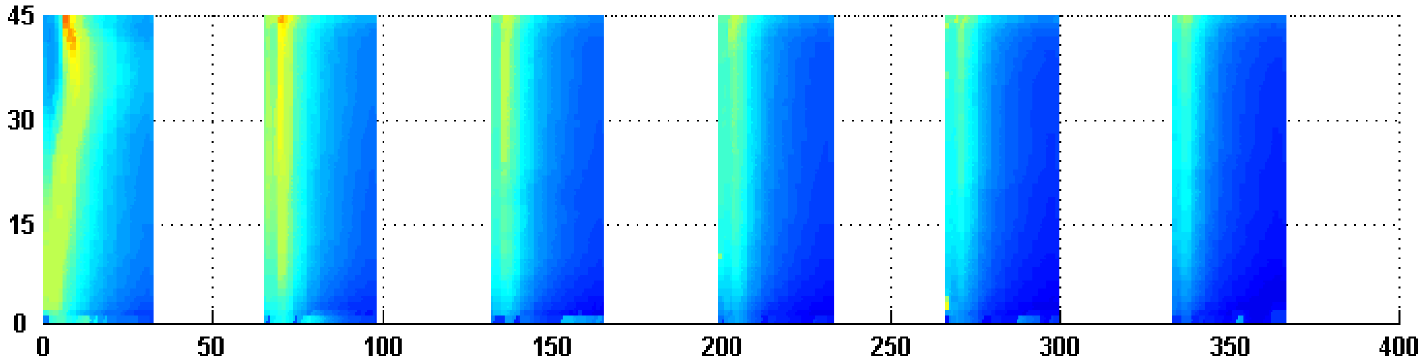
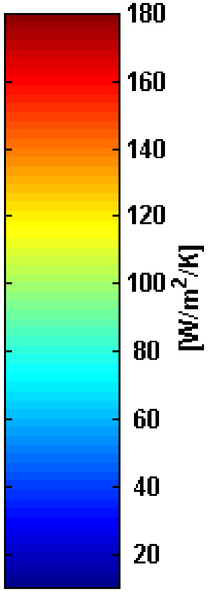
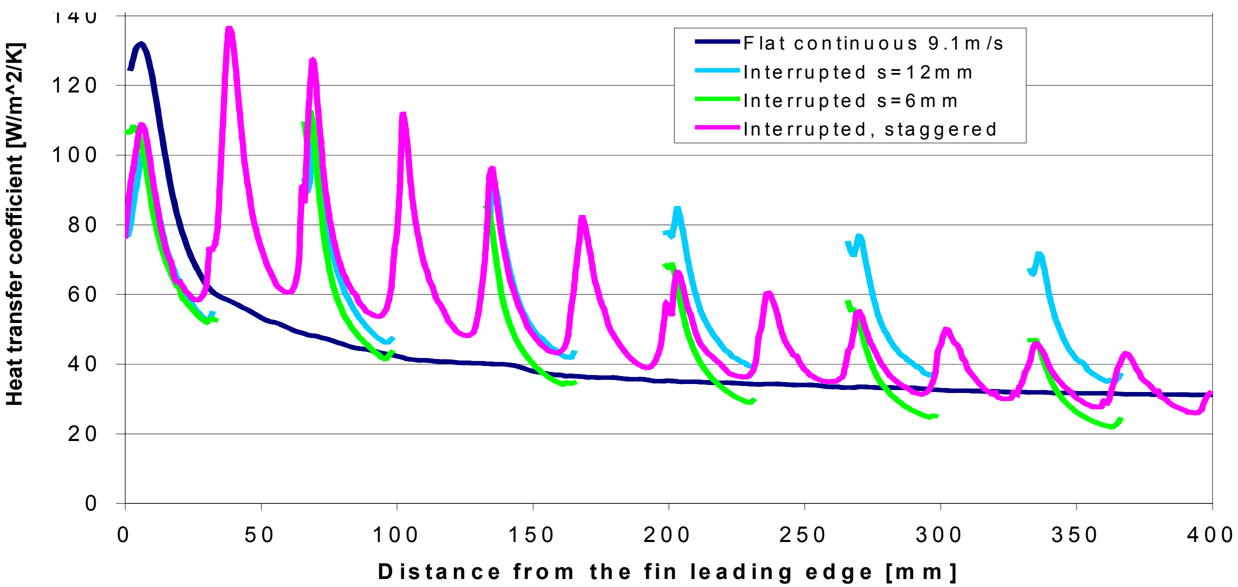


FIGURE 6

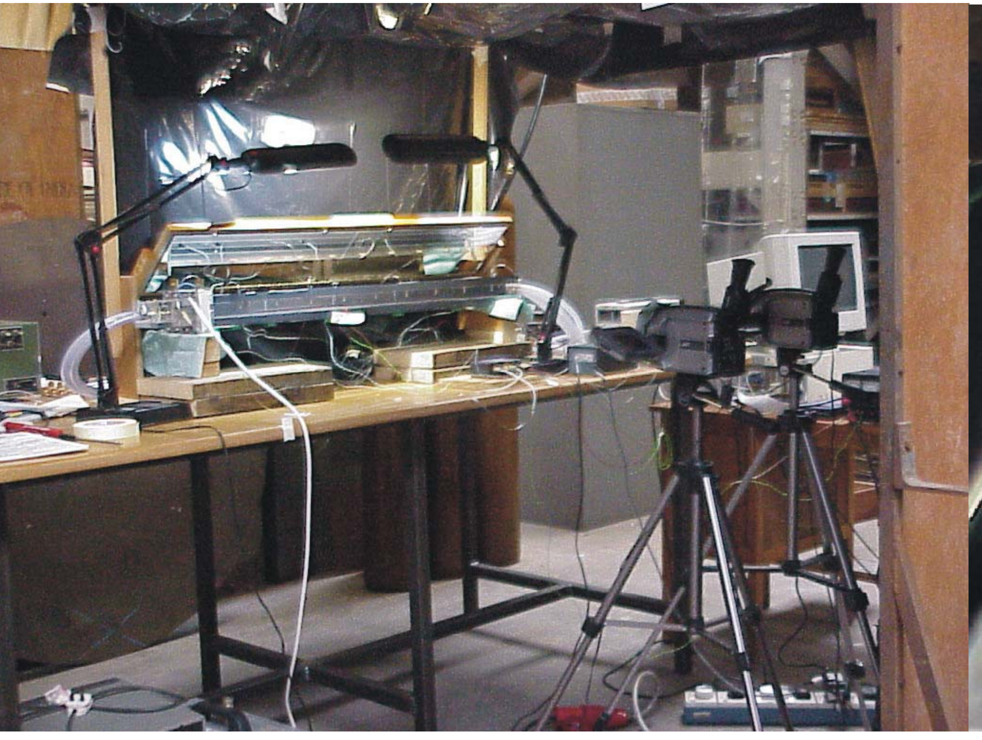
Earlier interrupted fin htc

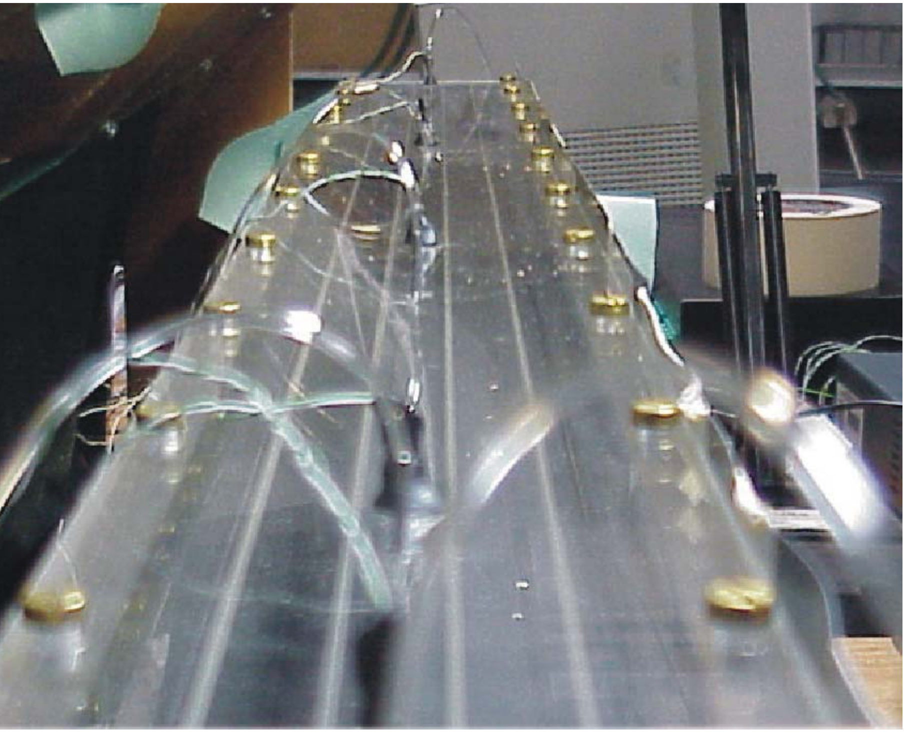




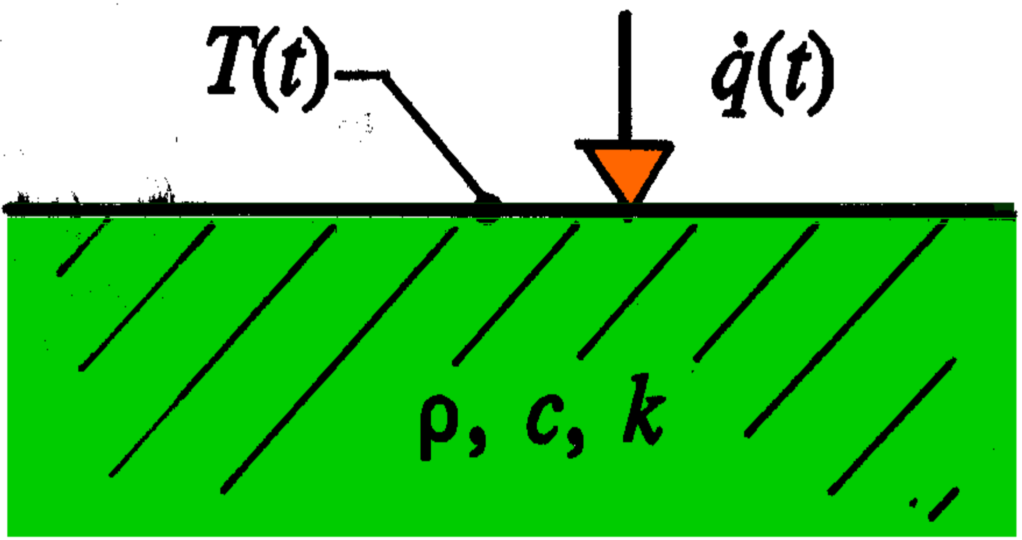


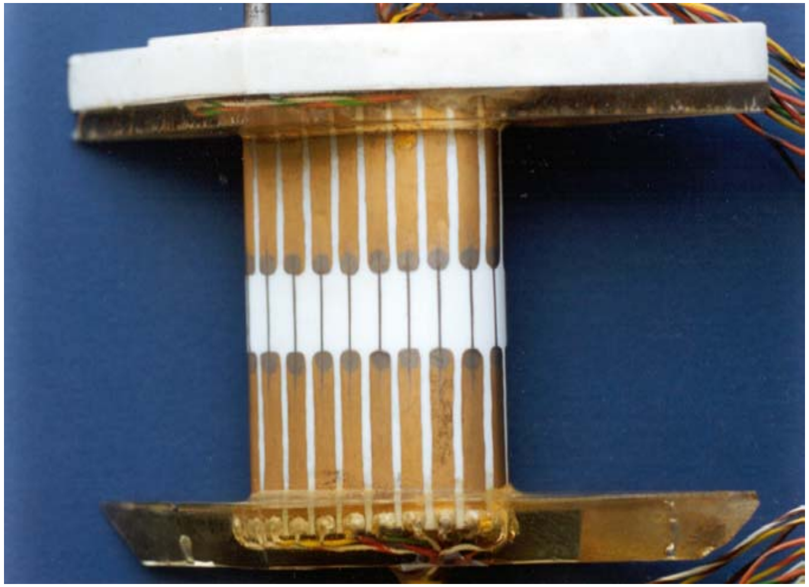
Recuperator heat transfer research underway

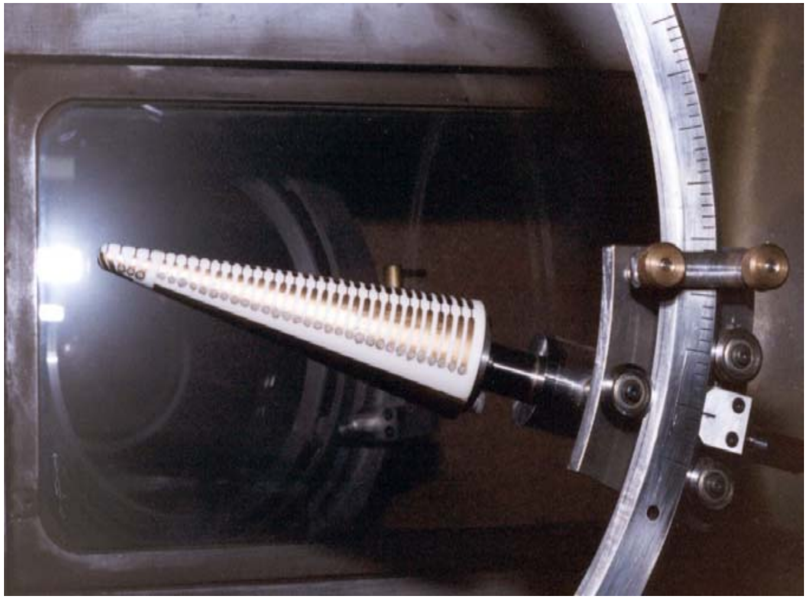




Early thin film gauges







DIFFUSION EQUATION

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{k}\frac{\partial T}{\partial t}$$

LAPLACE TRANSFORM

$$\dot{q} = \sqrt{\rho c k}\sqrt{s}\overline{T}$$

FREQUENCY

$$\dot{q}(\omega) = \sqrt{\rho c k}\sqrt{j\omega}T(\omega)$$

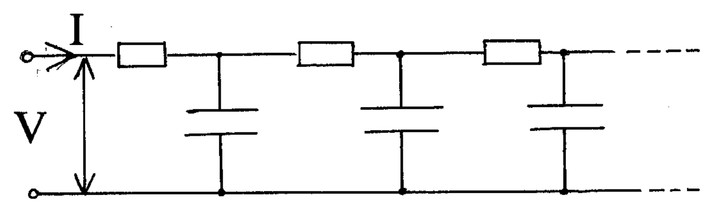
Analysis

$$T \rightarrow \dot{q}$$

$$\bar{\dot{q}} = \sqrt{\rho c k}\sqrt{s}\bar{T}$$

ANALOGUE

STEP $\dot{q}(t)$



$$\frac{\partial^2 v}{\partial x^2} = \frac{r}{c}\frac{\partial V}{\partial t}$$

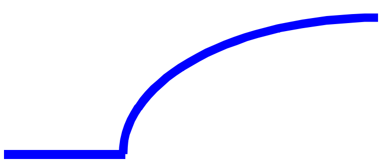
$$\bar{\dot{q}} \sim \frac{1}{s}$$

V≡T

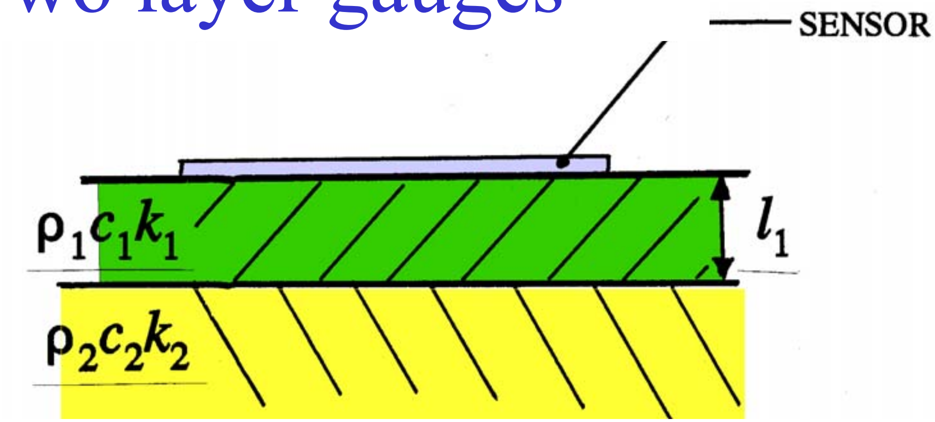
$$I \equiv \dot{q}$$

$$\bar{T} \sim \frac{1}{s^{3/2}}$$

$$T(t) \sim t^{1/2}$$



Two layer gauges

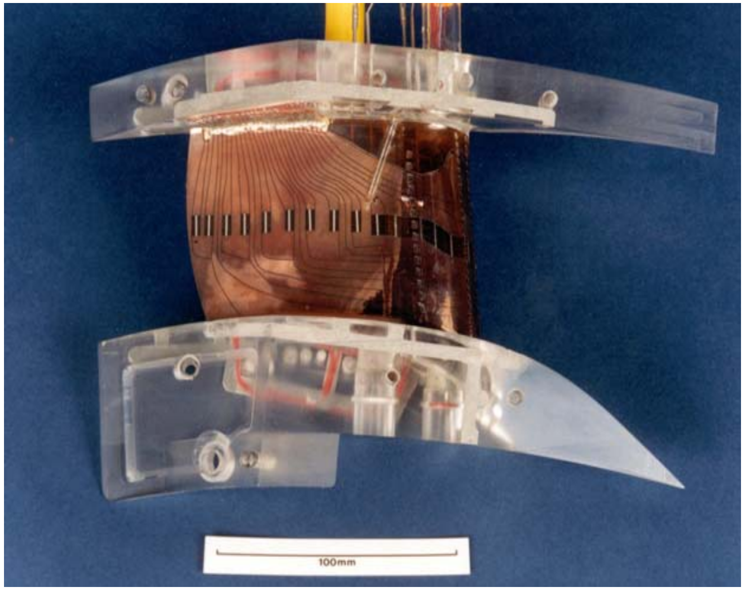


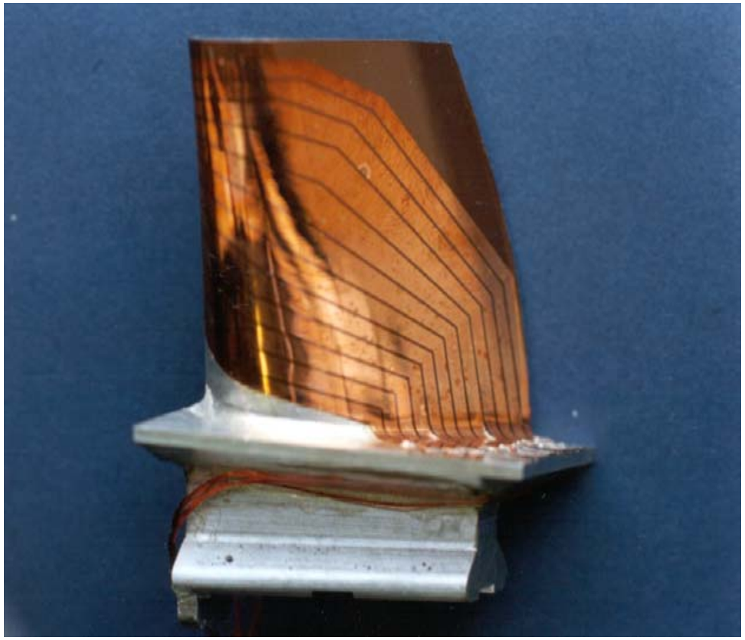
$$\bar{\dot{q}} = \sqrt{\rho_1 c_1 k_1}\sqrt{s}\,\bar{T}$$

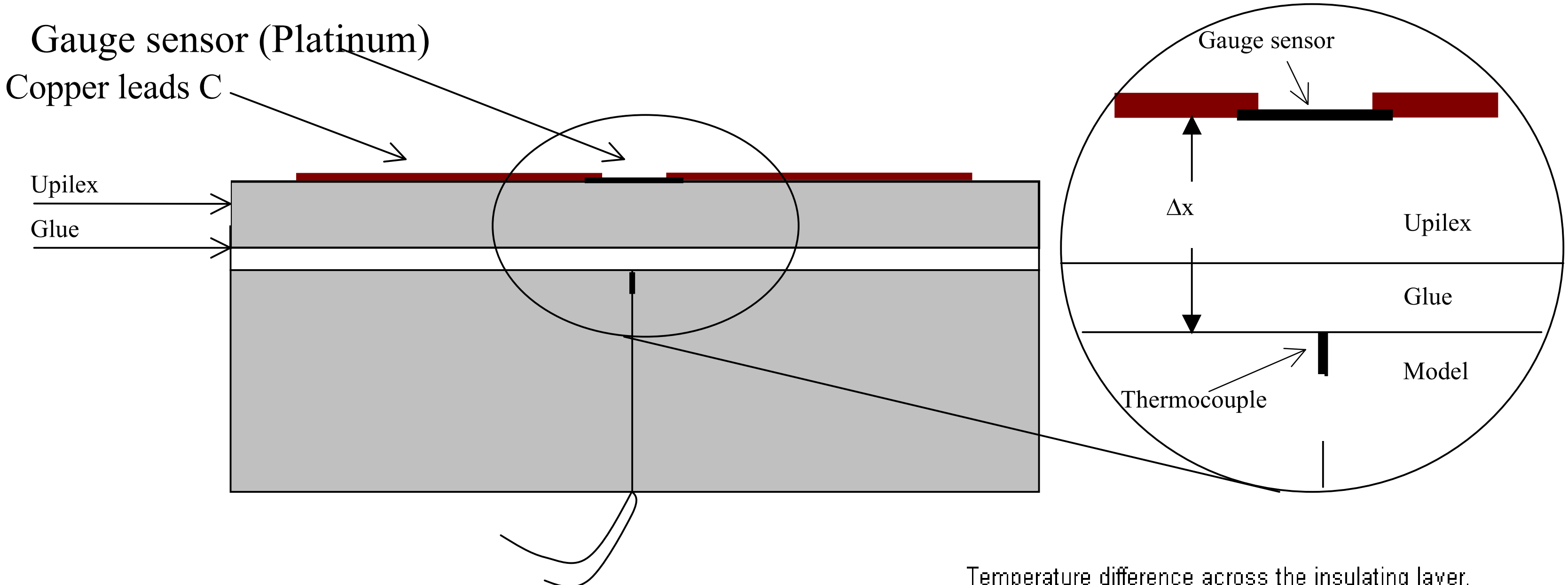
$$\mathrm{x}\left[\frac{1 - A\exp\left(-2l_1\left(\frac{s}{\alpha_1}\right)^{1/2}\right)}{1 + A\exp\left(-2l_1\left(\frac{s}{\alpha_1}\right)^{1/2}\right)}\right]$$

$$A = \frac{1-\sigma}{1+\sigma}$$

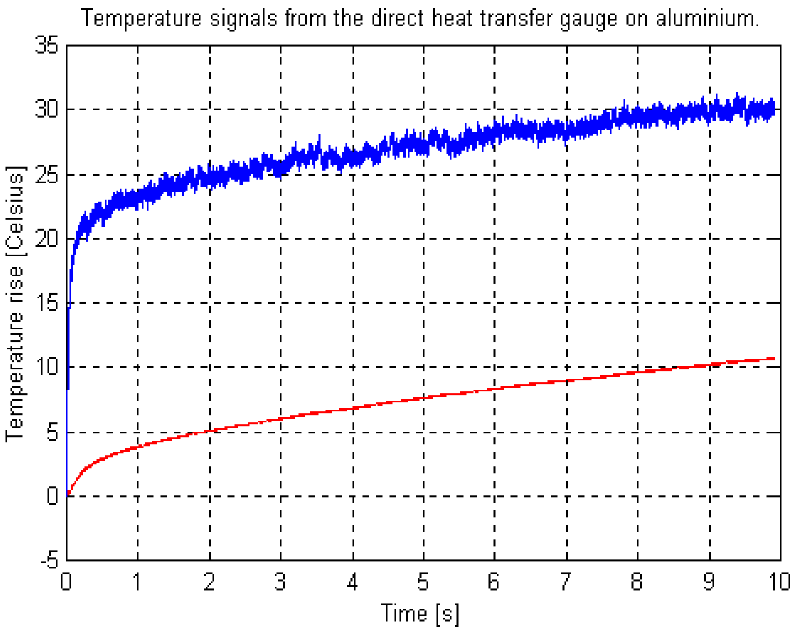
$$\sigma^2 = \frac{\rho_2 c_2 k_2}{\rho_1 c_1 k_1}$$



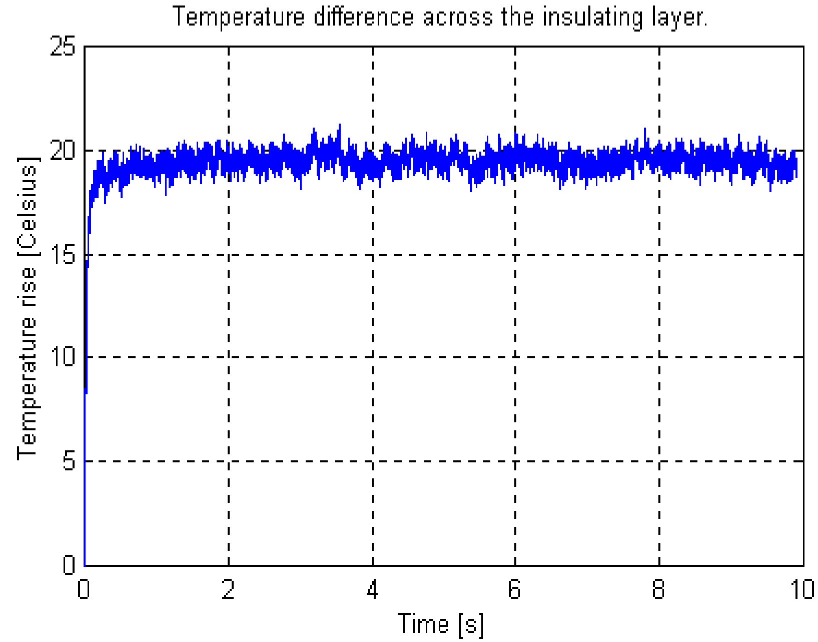




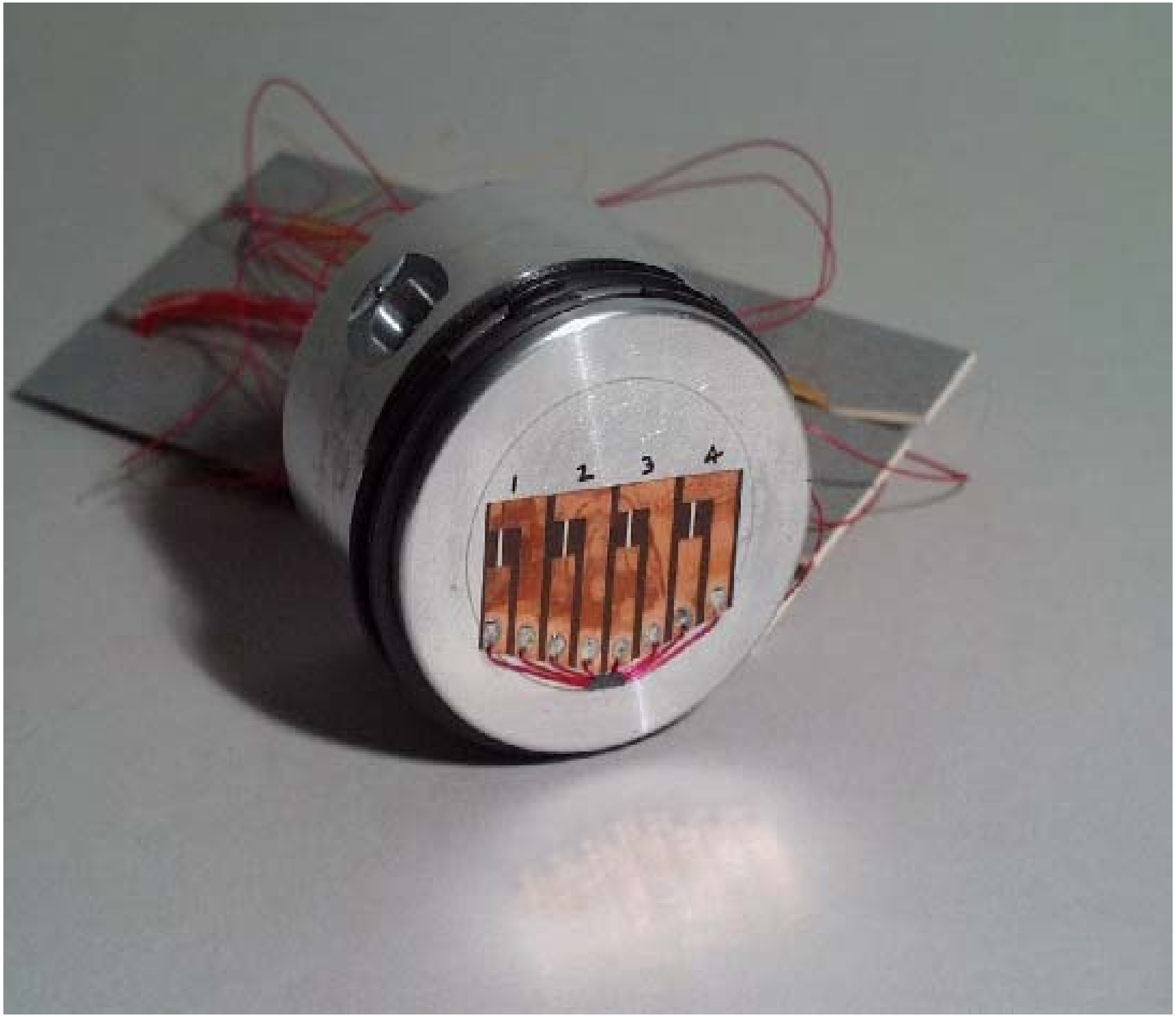
Gauge sensor (Platinum)
Copper leads C
Upilex
Glue
Gauge sensor
Δx
Upilex
Glue
Model
Thermocouple

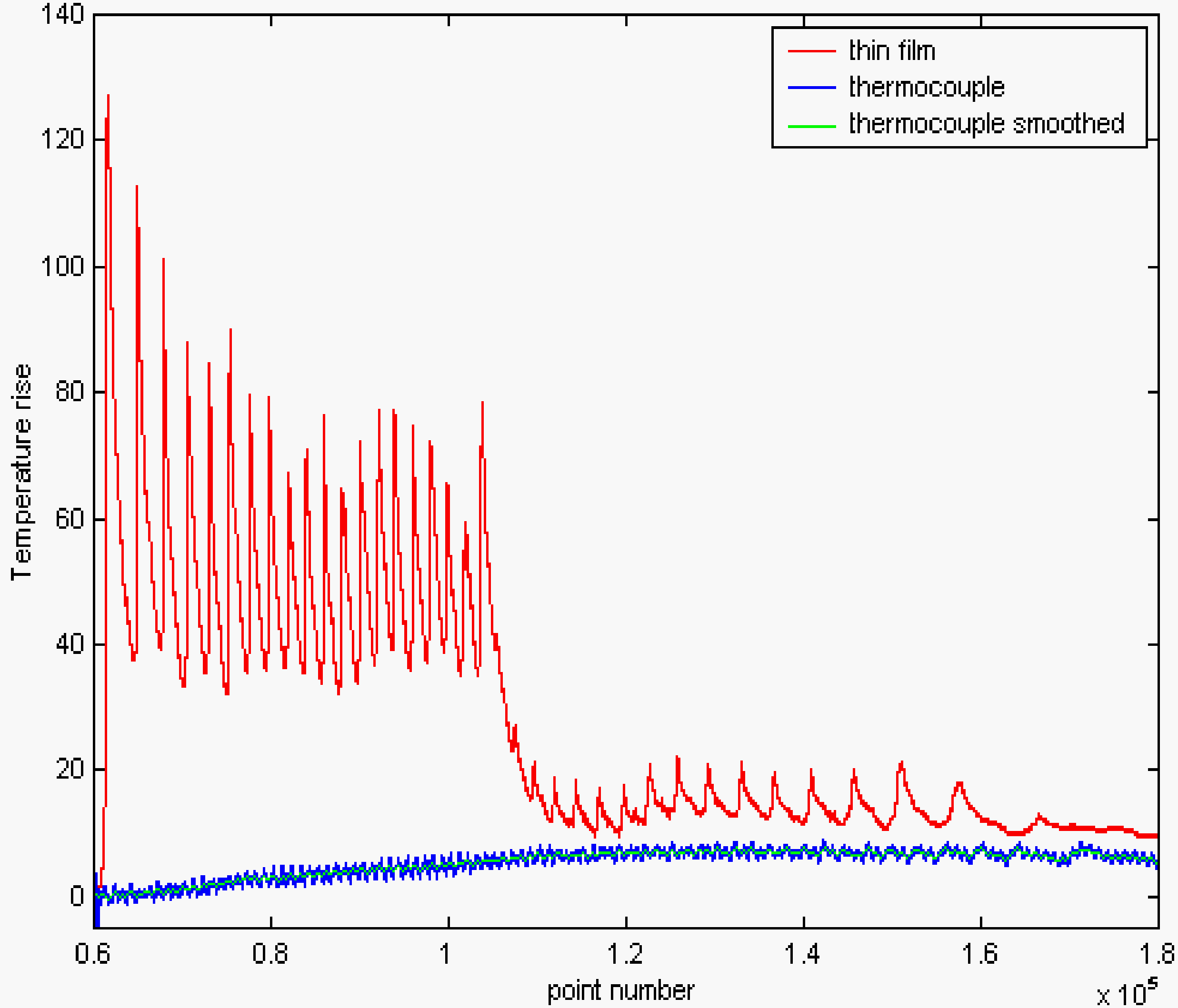


Temperature signals from the direct heat transfer gauge on aluminium.
Temperature rise [Celsius]
Time [s]

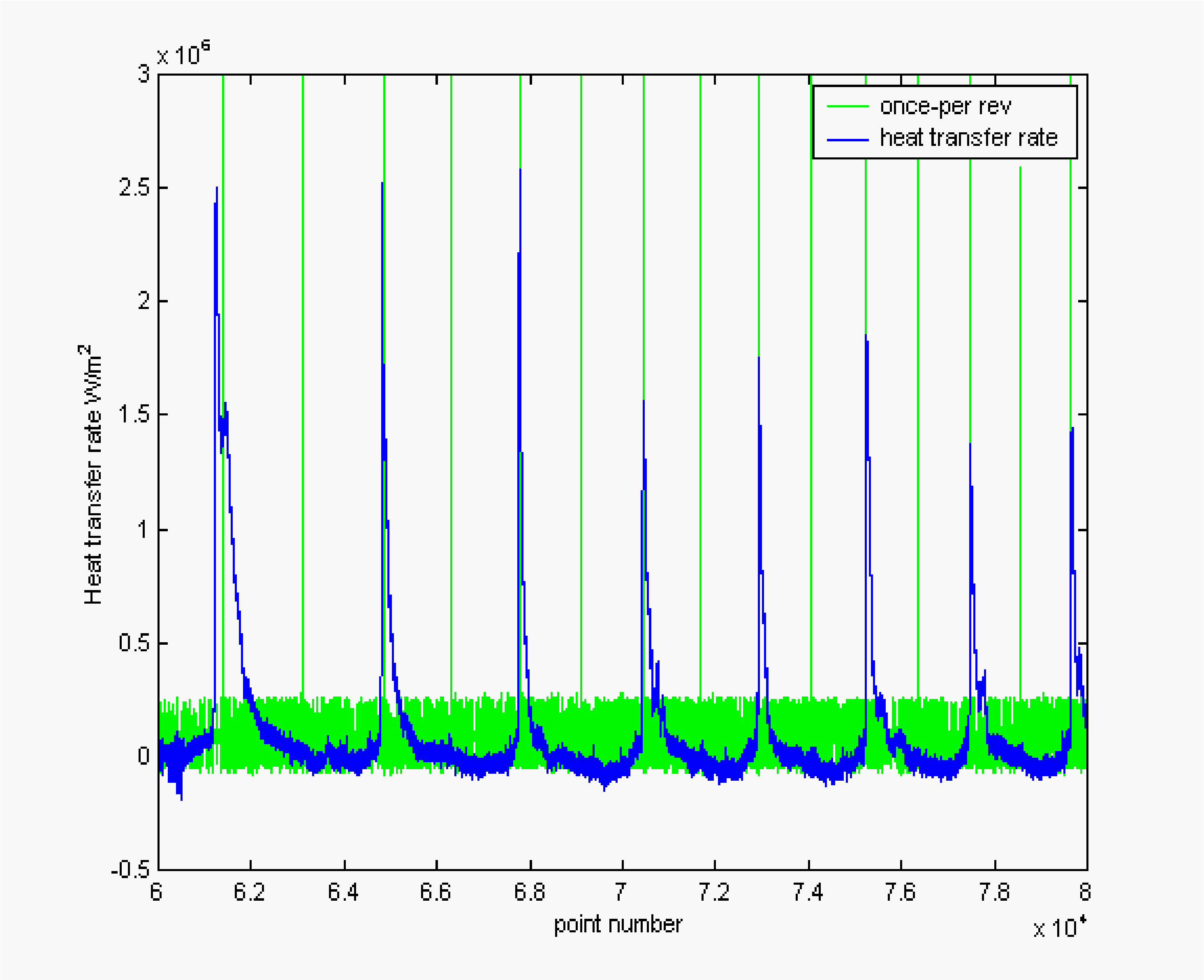


Temperature difference across the insulating layer.
Temperature rise [Celsius]
Time [s]


1 2 3 4

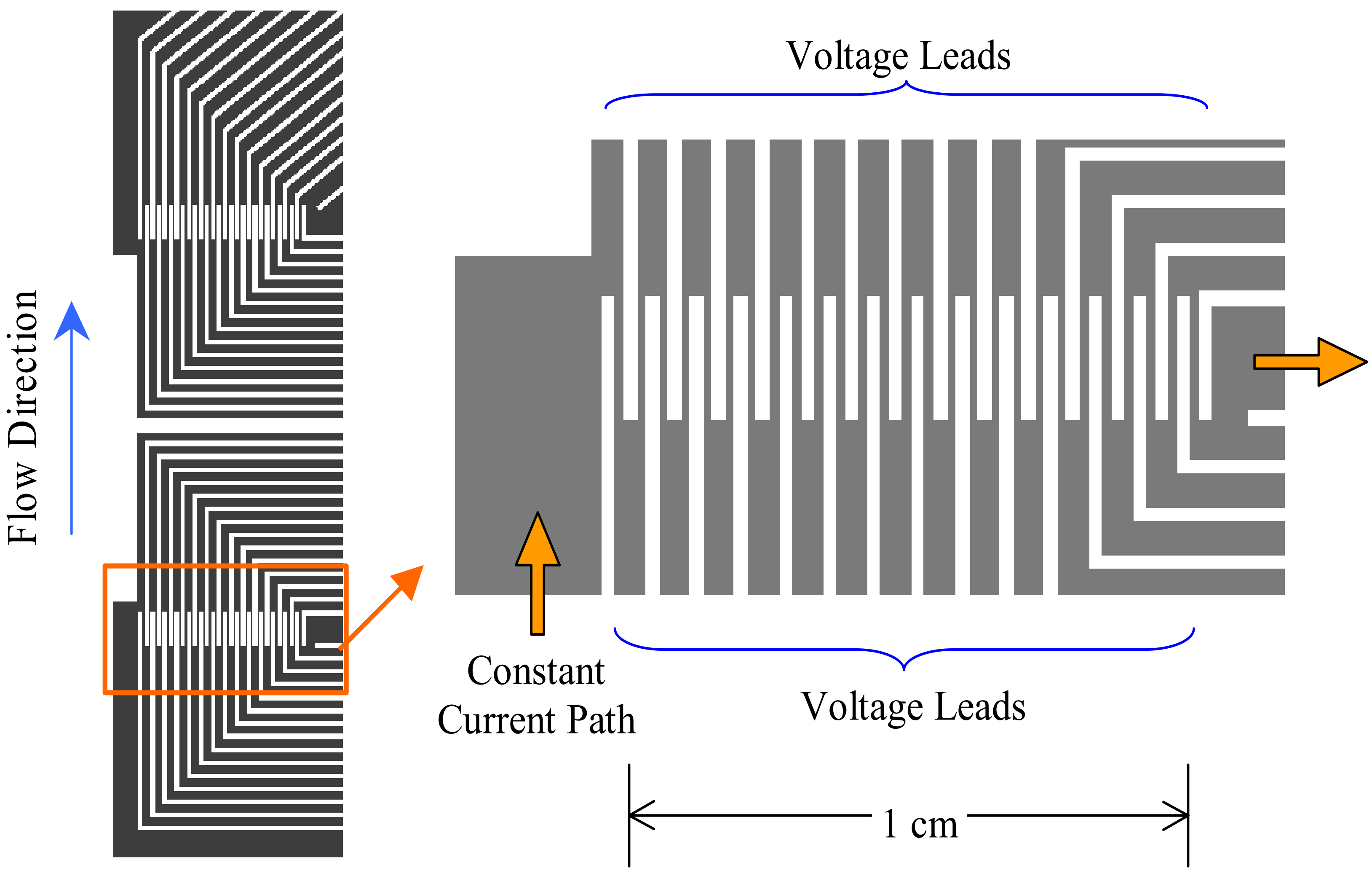


thin film
thermocouple
thermocouple smoothed
Temperature rise
point number
x 10^5
140
120
100
80
60
40
20
0
0.6
0.8
1
1.2
1.4
1.6
1.8

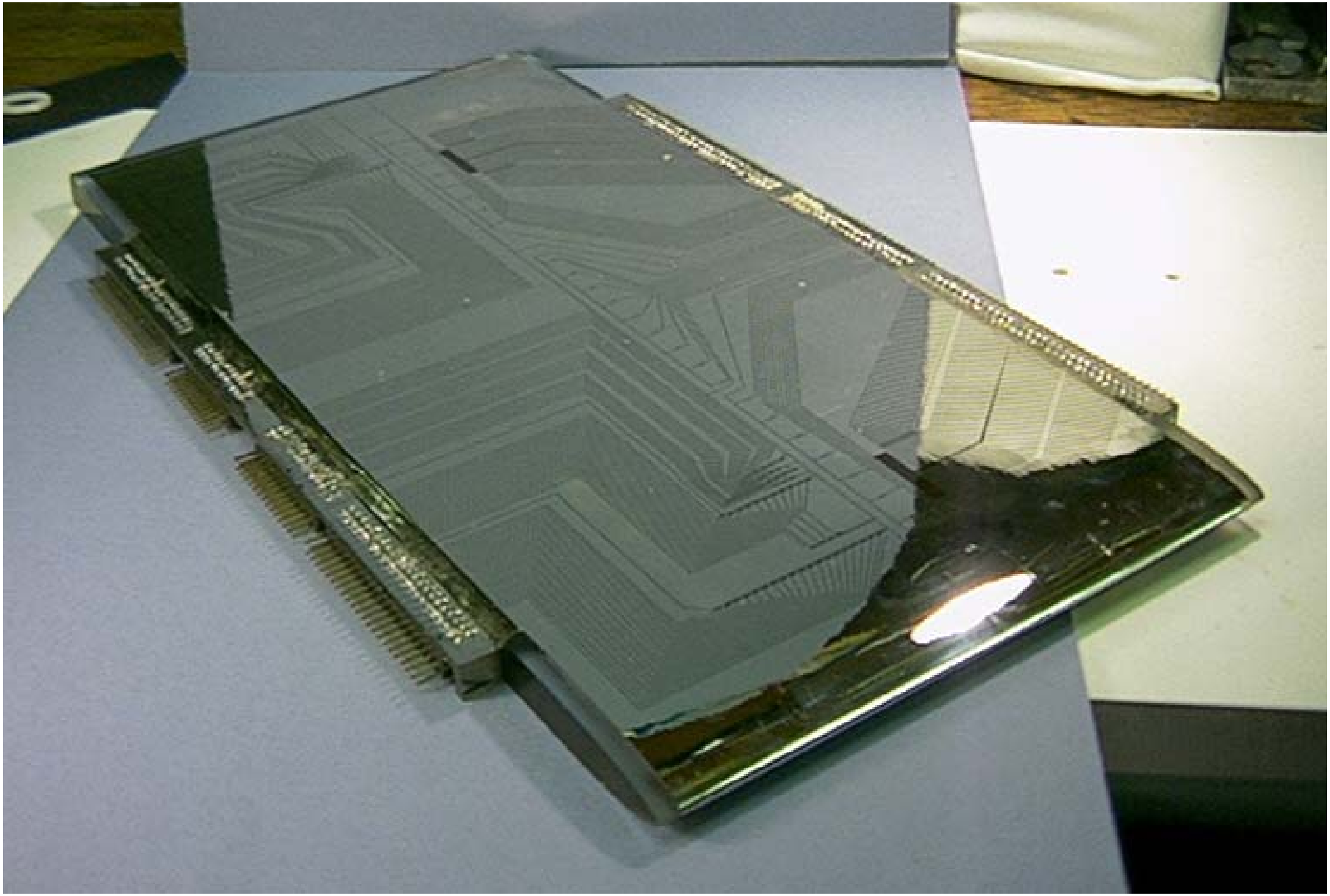


x 10^6
3
2.5
2
1.5
1
0.5
0
-0.5
Heat transfer rate W/m^2
6
6.2
6.4
6.6
6.8
7
7.2
7.4
7.6
7.8
8
point number
x 10^4
once-per rev
heat transfer rate

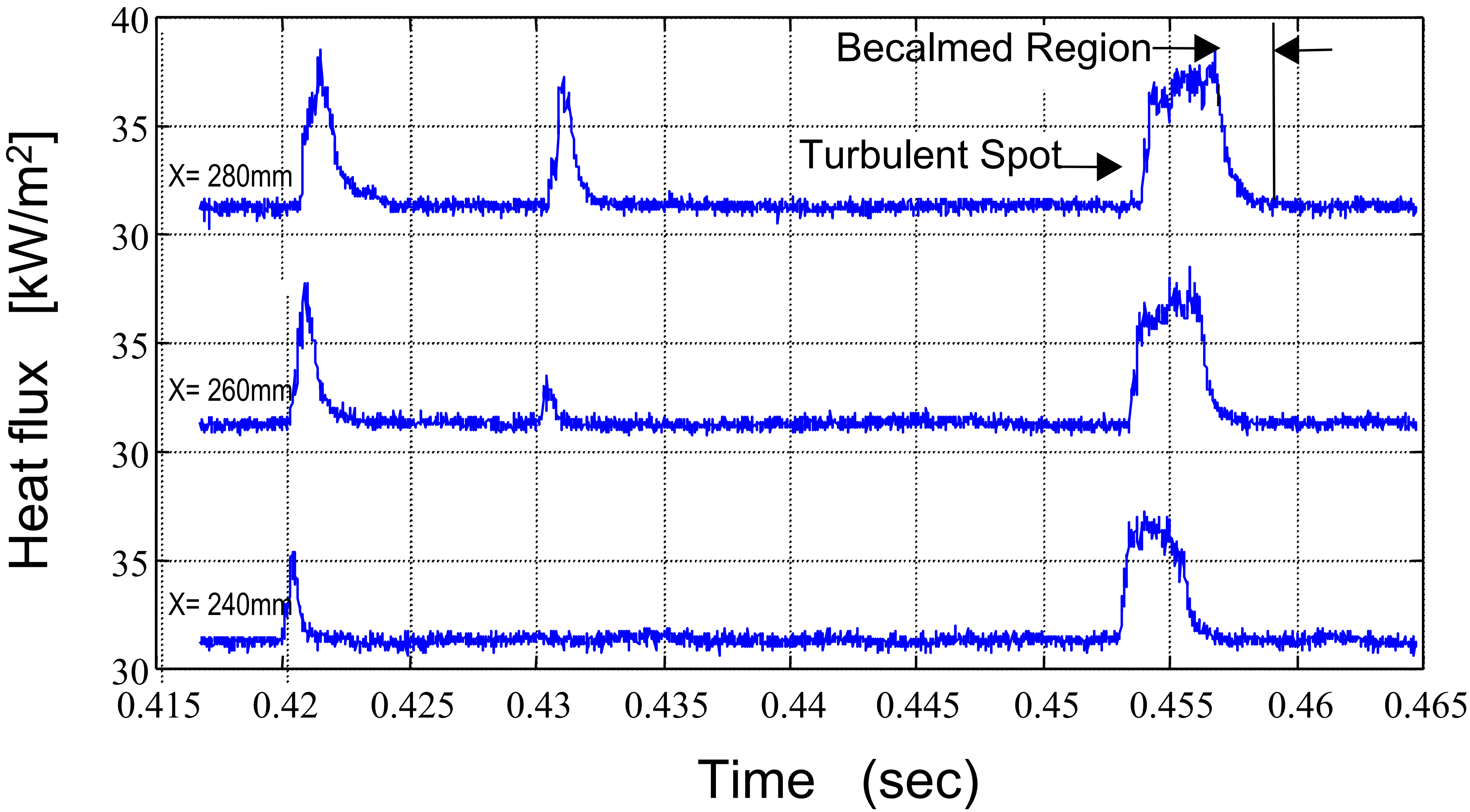
High Density Layout using Gauge Arrays



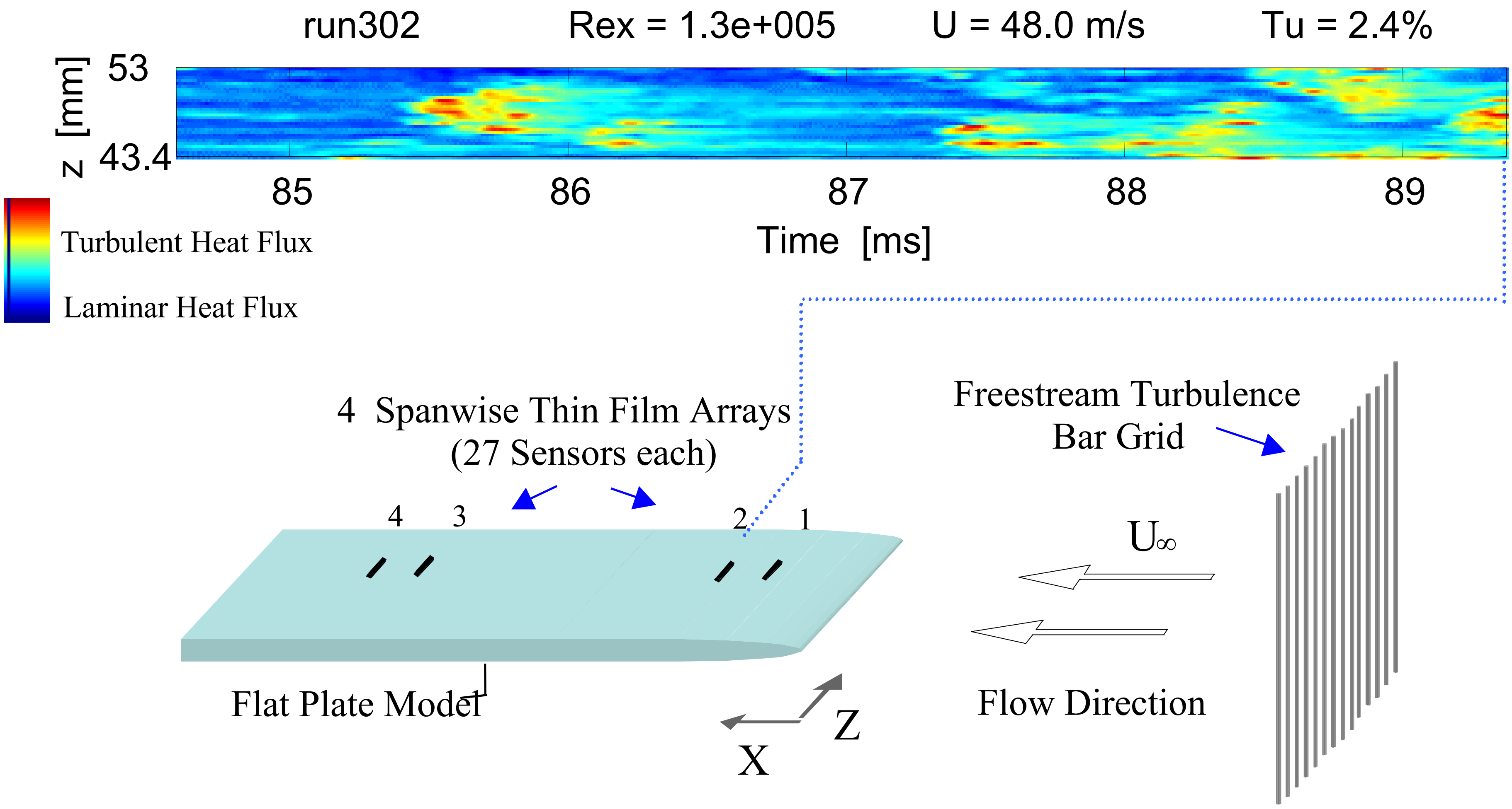
Model covered with sheet of TFG arrays



Turbulent Spot Detection with Surface TFG's



Visualizing Transitional Heat Flux



Conclusions

- Presentation of existing techniques for miniature measurements.
- Scaling can be useful for determination of convective loads at high resolution.
- Miniature thin film gauges being continuously developed.